Decision support framework for the allocation of production processes within multi-facility machinery manufacturing organizations

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **Management of Technology**

Faculty of Technology, Policy and Management

by

Mark Ellens

Student number: 4468090

To be defended in public on July 20th 2018

Graduation committee

Chairperson	: Prof.dr.ir. L.A. Tavasszy, Section Transport & Logistics
First Supervisor	: Ir. M.W. Ludema, Section Transport & Logistics
Second Supervisor	: Dr. M.P.M. Franssen, Section Ethics and Philosophy of Technology

Acknowledgements

This master thesis is the final step to fulfil my master Management of Technology of the Delft University of Technology. This thesis project is conducted for the Dewulf-group and the Technology, Policy, and Management department of the Delft University of Technology. I would not have been able to perform this thesis project without the help of some intelligent and dedicated people. Therefore, I am using this page to state my appreciation to them who assisted my in the completion of my thesis.

I would like to offer my special thanks to my first supervisor Ir. M.W. Ludema. The quality of this thesis improved significantly as a result of the ever-willing guidance during the many conducted meetings. His specialty in the field of supply chain management, and about how to conduct a design approach, allowed him to provide me with invaluable advice on the topic of this thesis. In addition to the contributions of Ir. M.W. Ludema, I would like to thank Dr. M.P.M Franssen, my second supervisor, for giving advice on the topic of decision-making. This has been of great help to improve the reliability of the results. And I would like to thank Prof.dr.ir. L.A. Tavasszy, the chairman of my committee, for sharing his knowledge on the topic of Multi-Actor Multi-Criteria decision-making and his enthusiasm for research on the topic of this thesis.

On the company front, I am greatly indebted to my colleagues from the Dewulf-group. Especially, Bertus Nobach and Jos Huisman, who guided me through the project and provided me with the required information. Furthermore, I want to express my appreciation to Ides Hauweele for giving me a warm welcome during my visit to Romania and for having lots of interesting discussions. Finally, I like to mention that I am very grateful for the opportunity to do my thesis in an organizational environment, especially because the organization operated in an industry in which I am really interested in.

Summary

Manufacturing organizations, with multiple production facilities, have the tendency to distribute specific production processes to certain facilities. Common executed production processes comprise: metal working, welding, painting, and assembling. Usually, the distribution of these production processes among the facilities of the organization developed over time. In some cases, the current distribution does not maximally satisfy the goals and objectives of the organization. Hence, there is room for improvement, and it is desirable to distribute the production processes optimally resulting in the achievement of a higher degree of satisfaction of the goals and objectives. Questions that may arise are: how to increase the compliance of the goals and objectives by relocating the production processes? What is of importance and exercises influence considering the decision-making regarding the relocation of production processes? Who are involved in the decision-making process? The main research topic of this thesis revolves around the optimization of the compliance to manufacturing organizations' goals and objectives. Hence, this report aims to answer the summarized questions above by developing a decision support framework in great detail.

The allocation problem has several aspects to consider. The first aspect being that the allocation problem has a high level of complexity. The complexity is due the number of facilities, production processes, and decision variables. Examples of decision variables are, labour costs, quality of the product, and process time. The problem cannot be solved by allocating the production processes to the facility that offers the lowest costs as is emphasized in multiple readings. The second aspect is that the allocation problem is not a greenfield problem (i.e. a problem without the need to consider the current situation), since the allocation of production processes happens among existing facilities. In addition, existing supply chain networks must be taken into account by managers during the decision-making process. Another aspect is that multiple stakeholders are involved in the decision-making process, and each of them attach a different importance to the decision criteria. Although considering multiple stakeholders is crucial, it does increase the complexity and overall difficulty of the decision-making process. The final aspect is that the allocation problem involves a lot of uncertainties. The decision variables have a dynamic behaviour which is difficult to predict.

Without a structured approach it is difficult to create a complete overview of these aspects. In this thesis a decision support framework is developed since a structured approach for the allocation problem that considers all these aspects does is not yet in existence. The design objective of this thesis could therefore thus be frames and is thereby: *Develop a decision support framework that can be used by multi-facility manufacturing organizations to allocate their production processes in order to satisfy the goals and objectives of the organization.*

The framework is developed by following a designing approach and iteratively improved by executing it on a case study at the Dewulf-group. The Dewulf-group is an agricultural machinery manufacturer with multiple facilities in Europe. The framework is built by adjusting and combining existing methods into a step-by-step approach that managers can exploit. The framework consists of the following ten steps:

Step 1: Define production processes
Step 2: Define facilities
Step 3: Stakeholder analysis
Step 4: Define and analyse influencing variables

Step 5: Develop scenarios
Step 6: Simulate performances on the criteria
Step 7: Valuation of the performances on the criteria
Step 8: Define criteria weights
Step 9: Allocate production processes
Step 10: Decision-making

The first two steps define which production processes and facilities are included in the analysis. The third step identifies the stakeholders and their goals and objectives. The objectives have to be transformed into criteria on which the final analysis will be based. In step four, the influencing variables are identified and analysed. Thereafter, in the fifth step, multiple scenarios are developed. These scenarios are based on dominant themes. In each scenario certain variables are changed based on this theme. Then, in step six, all the production processes should be simulated at each facility for each of the scenarios. The simulation should show the performances on the criteria of performing the processes at the facilities. This should be done in a spreadsheet simulation based on the decision variables. Accordingly, in step seven, the performance on the criteria should be valued with a score. Step eight defines the criteria weights of the stakeholders by using the Best-Worst Method. The Best-Worst method is a method that assigns weights to criteria based on the importance stakeholders attach to it. Followed by step nine, these criteria weights are multiplied with the performance scores. Then, each production process is allocated at a facility at which they achieve the highest weighted performance score. In the final step, the allocation is transformed into data that can be used by managers making long-term and short-term decisions. For long-term decision-making (e.g. investment decisions), managers benefit from seeing the big picture. This can be achieved by presenting graphs about the total distribution of the production processes. For short-term decision-making (e.g. make-or-buy decisions), managers benefit from a simple set of rules that can be used to select a facility to perform a production process.

The ten steps of the framework are executed on an allocation problem of the Dewulf-group. The results are of great use for the organization. Due to the framework discussed in high detail in this report, they are able to make substantiated decisions about the allocation of their production processes.

Table of content

1. Introduction

1.1 Background

Big machinery manufacturing organizations that produce a diverse set of products often have multiple production facilities (multi-facility). These production facilities, sometimes even located in different countries, face different circumstances in terms of labour costs, distance to suppliers and customers, availability of skilled employees, quality of the labour force, and many more (MacCarthy & Atthirawong, 2003). Besides these facility characteristics, production processes performed at the facilities can also vary in characteristics like process time, product dimensions, difficulty of the process, and so on. Both facility and production process characteristics (hereinafter called variables) have to be taken into account when organizations want to allocate production processes to their facilities. With 'allocation' is meant that organizations choose which production processes they want to perform at each of their facilities. In the broadest sense, production processes can be defined as all the tasks and activities that together transform into products (Garvin, 1998, p. 33). In this thesis project the focus is on the main production processes performed by machinery manufactures, i.e. metal working, welding, painting, and assembling processes. Making decisions about the allocation of these production processes among multiple facilities is a key aspect of strategy and logistical decision-making for manufacturing organizations (MacCarthy & Atthirawong, 2003). Making the right decisions may offer a more efficient or effective supply chain the organization's products and so create a competitive advantage. A supply chain is a set of firms that pass materials forward. Normally, several independent firms are involved in this process (Mentzer, et al., 2001, p. 3). However, in this thesis project the set of firms can also be dependent firms within the organization. The supply chain is therefore determined as all involved activities in the production of products from the supply of semi-manufactured goods until the sale of finished products. Semi-manufactured goods are steel plates, tubes, beams, etc. The extraction of raw materials is excluded because it is not of relevance for most manufacturing organizations.

Organizations are interested to allocate production processes at another facility if it contributes to their objectives. As an example, if allocating a production process in facility A instead of B decreases the costs of the final product, and the organization's objective is to decrease the product costs, they would certainly be interested to do this. Although many organizations make allocation decisions solely based on cost-related variables, many other variables should also be considered when making these kind of decisions (Dale & Cunningham, 1984).

The allocation decision of production processes is not a greenfield decision, i.e. making a decision without considering the current situation. The decision which is focused upon in this thesis project is the decision to allocate production processes among existing facilities. Furthermore, the problem is a multi-stakeholder problem, since it involves multiple individual production facilities within one organization. As mentioned, the decision involves variables more than just cost-related variables. These variables can be both quantitative and qualitative. In addition, the problem is multidisciplinary in nature because it involves aspects of supply chain management and decision-making disciplines.

All these above-mentioned aspects make the allocation decision rather complicated and thus hard to decide on. A systematic approach of how to execute such decision-making processes which include all the aspects does not yet exist. The aim of this thesis project is therefore to develop a decision support framework which can be used by machinery manufacturers to allocate their production processes among their facilities. The framework will provide managers with a systematic approach to execute this decision and so guide this difficult decision-making process.

1.2 Relevance and contribution

According to Fahimnia et al. (2013), there is a growing trend in the number of manufacturing organizations which join larger existing supply chain networks. Furthermore, new established organizations often have more than one production facility. They therefore mention the need for the development of more multi-facility decision supporting tools that simulate today's supply chains characteristics. Vidal and Goetschalckx (1997) agree with this trend and denote the need for the development of specialized methods (e.g. for machinery manufactures organizations), since it is almost impossible to develop a general method that integrates all industry specific aspects.

Several mathematical models to calculate an optimal allocation of production processes among existing production facilities exist (e.g. (Fleischmann, Ferber, & Henrich, 2006) and (Hax & Meal, 1973)). The problem of these models is that they only include a limited number of quantitative variables, such as labour and transportation costs. Dale and Cunningham (1984) reported that decisions about production locations are almost always based on costs, but that such decisions rarely depend solely on cost variables. Qualitative variables such as quality of suppliers, reliability of the labour force, and company culture cannot be ignored during the decision-making process of allocating production processes (MacCarthy & Atthirawong, 2003). Delis et al. (2017) showed evidence that firms who allocated production processes in foreign country facilities re-allocated these production processes to the domestic country more often after the financial crisis of 2008. Reasons that organization re-allocated these processes are that the requirements of the product or processes could not be fulfilled, they underestimated important variables into the decision, or perceived rapidly increasing costs in the foreign country. Reasons for this are that because organization perceived requirements of the product could not be fulfilled, an increased insight on the production characteristics of low wage countries, or a more detailed view on the actual costs of allocating production processes (Snoo, 2016). This provokes the idea that the initial decision to allocate the production process is not based on sufficient variables. Dale and Cunningham therefore suggest that a systematic approach should be developed that guides this decision-making process based on careful weighing of the key variables involved.

Besides failing to include multiple quantitative and qualitative variables, existing methods do also underestimate the different objectives among the stakeholders within the organization. Facilities in an organization frequently have different, conflicting objectives. For example, facilities which produce components for other facilities benefit from making large production batches. This typically conflicts with the objective of other facilities' warehouses to reduce inventory (Simchi-Levi & Kaminski, 2000). Including the different objectives of stakeholders is crucial in problem solving and should therefore also be included in the decision-making process about production process allocation (Bryson, 2004).

Individual methods to make decisions based on carefully weighting of the key variables (e.g. BWM (Rezaei, 2015)) and making decisions based on the objectives of multiple stakeholders (e.g. MACMA (Macharis, De Witte, & Ampe, 2009)) do exist. However, a systematic approach which combines these methods in a supply chain environment does not yet exist. The decision support framework which is developed in this thesis contributes to the field of supply chain management by filling up this gap. Multi-facility machinery manufacturing organizations can use this framework to guide the decision-making process of the production allocation and be able to make the final decision based on relevant variables, stakeholder objectives, and multiple scenarios.

1.3 Thesis outline

The remainder of this thesis exists of seven chapters. The second chapter will set out the design methodology. This is done by discussing the design objective and design process. The design itself proceeds in chapter three and four. The third chapter defines the problem and requirements and the fourth chapter describes the development of the framework. In the fifth chapter, this framework is executed on a case study. Chapter six describes the validation of the framework which is done by three sensitivity checks and elaborating on the user feedback of the case study results. Concluding, the seventh chapter discusses the results and the eight chapter offers the conclusion and gives recommendations for further research.

2. Design methodology

This chapter discusses the design methodology of this thesis. First, the design objective is discussed. Next, the scope of the project is defined. Third, the deliverables of the project are discussed. Finally, the design process that is used to develop the framework is explained.

2.1 Design objective

The aim of this thesis is to develop a framework that provides a systematic approach for multi-facility machinery manufacturing organizations to allocate their production processes within the organization. The framework should help organizations to improve the supply chain of their products according their own goals and objectives. The design objective is formulated as:

Develop a decision support framework that can be used by multi-facility manufacturing organizations to allocate their production processes in order to satisfy the goals and objectives of the organization.

The goals and objectives will be different for each organization. Some organizations are more costs focused than others, whom might be more quality focused. The reason to develop a framework instead of a method is because a framework allows for more flexibility than a method. Methods are more applicable when multiple similar processes have to be performed in a coherent, consistent, and accountable manner (Draffin, 2010). For the purpose of this thesis, a loose and flexible framework is more applicable because the process is highly dependent on the goals and objectives of the organization. More about the characteristics of a decision support framework is described in section 3.2.

2.2 Scope of the project

To define the scope of the project, both the design process and the framework itself are discussed.

2.2.1 What will and what will not be part of the design process?

Developing the decision support framework, including the required methods and tools to execute the framework, will be part of the design process. Furthermore, the decision support framework will be executed on one case study. Extensive testing of the framework on multiple cases will not be part of the design process due to a lack of time. However, multiple 'what if' scenarios will be performed on the case study in order to check the sensitivity of the framework.

2.2.2 Who can use the decision support framework?

The framework is intended for machinery manufacturing organizations with multiple production sites whom need a structured way to allocate production processes to their facilities. Managers, decision-makers, researchers, consultants, interns, or employees of the organization (hereinafter called managers) can use the framework to facilitate this whole decision-making process. Important to mention is that the framework will act like a decision support tool, not a replacement of the decision-maker function. The output of the framework can be used to make substantiated decisions about the allocation of production processes among multiple facilities.

2.3 The deliverable

The deliverable of the thesis is a decision support framework. This framework is a roadmap of several steps that managers should execute. A skeleton of the empty framework is shown below in figure 1. At the end of the thesis, the framework is filled in so it provides manufacturing organizations with a step-by-step approach with activities to execute each step. Some of these activities are based on existing methods like the Multi-Actor Multi-Criteria Analysis or the Best-Worst Method. Other activities are developed from scratch.

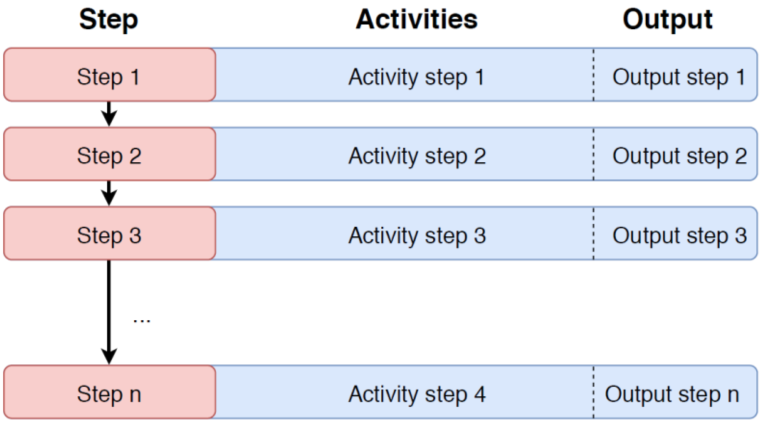


Figure 1: Skeleton of the decision support framework

2.4 The design process

Figure 2 visualizes the design process of this thesis project. This process is based on the engineering design process described by Dym et al. (2009). The process started with defining the allocation problem of multi-facility organizations. This is done by a literature review of general aspects of the problem. These aspects are translated into requirements for the framework. Next, the conceptual design emerged from evaluating existing methods that fulfil part of the requirements of the framework. All these methods are combined into a decision support framework for the allocation of production processes. Accordingly, a step-by-step explanation is made which led to a detailed design. Next, the framework is validated by user feedback. This is done by using the framework on a case of the Dewulf-group. The Dewulf-group is an agricultural machinery manufacturer with multiple facilities in Europe. During the case study, all the steps are executed in order to provide the managers with data, with which they can make better decisions regarding the allocation of certain production processes. Finally, multiple 'what if' scenarios are executed in order to check the sensitivity of the framework.

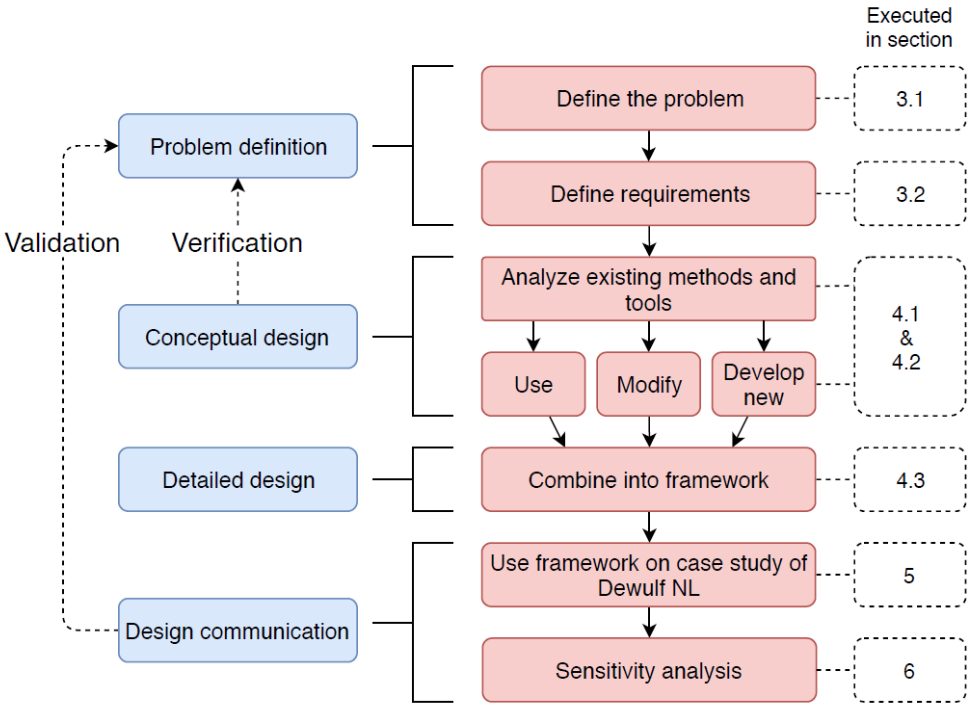


Figure 2: The design process. Adapted from Engineering Design: A Project-Based Introduction (p. 26), by C. Dym, P. Orwin, E. Spjuit, (2009), New York: John Wiley & Sons.

Although the framework emerged from the literature, it is adapted several times due to feedback from the case study. The number of cycles needed to reach the final outcome depend on the progression of the development (Sein, Purao, Henfridsson, & Rossi, 2011). This iterative process generated incremental improvements to the framework. In the case of this thesis the process is at least repeated until the framework fulfilled the requirements and it provided Dewulf NL with usable information for the decision-making process.

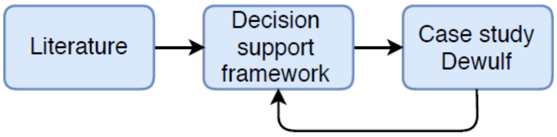


Figure 3: Iterative process of the development of the framework

3. Problem definition and requirements

3.1 The problem

To define the problem, the major aspects of the production process allocation problem are discussed. A literature review is done to identify and analyse these aspects. Aspects are found in literature about supply chain management, multi-criteria decisions, multi-stakeholder decisions, decision-making in organizations, and risk and uncertainty in supply chain decisions.

3.1.1 The complexity of the allocation problem

A mathematical representation of the problem is described in order to raise awareness of the complexity of the problem. The set of production processes that needs to be allocated can be expressed as:

$$P = \{ p_1, p_2, p_3, \dots, p_n \}$$

The set of possible facilities where these processes can be performed can be expressed as:

$$F = \{ f_1, f_2, f_3, \dots, f_n \}$$

Each production process p has to be allocated to one of these facilities. Put differently, each production process is a sub-problem. Each sub-problem is affected by both production-process-related and facility-related variables like labour costs, transportation costs, product dimensions, quality of the labour force, etc. The set of variables can be expressed as:

$$V = \{ v_1, v_2, v_3, \dots, v_n \}$$

The decision on each of the sub-problems will affect the performance of the supply chain. An example of the impact on the supply chain of such a sub-problem is visualized in figure 4.

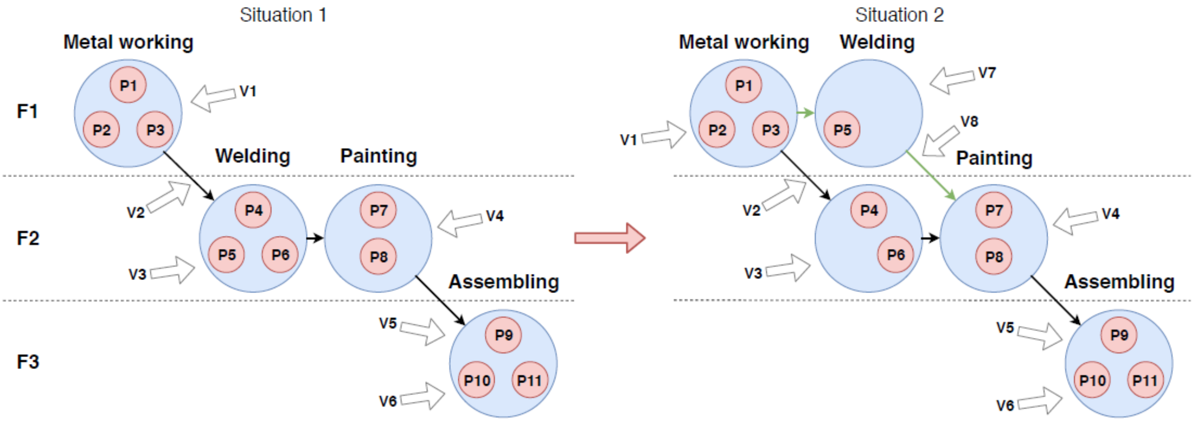


Figure 4: Example of the supply chain impact of shifting one production process

In this example welding process p_5 is moved from f_2 to f_1. This has an impact on the labour costs of p_5 (v7), the transportation costs between the facilities (v2 and v8), and the delivery time at f_3 (v6). Note that production processes of one type (i.e. metal working, welding, painting, and assembling) do not entirely have to be performed in one facility. It is for example possible that the most satisfying outcome can be achieved by performing some welding processes in facility 1 and some in facility 2. Also note that the production processes of one type can be performed parallel but all have to be finished before the next type can start. So, metal working, welding, painting and assembling processes are performed sequentially. This entails that multiple welding activities for one product can be performed at the same time but will together move to the painting area.

For each production process in set P the decision should be made to which of the facilities in set F it should be allocated. The challenge is to find a combination of solutions which leads to the most satisfying outcome for the organization. The number of combinations can be expressed as:

$$Number\ of\ combinations = F^P$$

In practice, the number of possible combinations does not always equal F^P. Due to capacity and capability restrictions some production processes cannot be performed at a particular facility. The identification and inclusion of these constraints should be part of the framework.

It is possible to manually calculate and compare the outcomes of the allocation of two or three processes among two facilities (four and eight solutions respectively), but when more processes or facilities will be included manual comparison becomes extremely difficult and time consuming. The framework should therefore propose an approach that can be automated and whereby variables are easily updatable without redoing lots of manual calculations. Moreover, when some new production processes are introduced due to the development of new machines, it should not be needed to walk through the whole framework once again. The results of the framework should be transferable into easy-to-use rules to decide the location of production processes.

3.1.2 Not a greenfield decision

As mentioned, the allocation decision, which the framework aims to support, is not a greenfield decision. Production processes are allocated to existing facilities. Before being able to see the impact on the supply chain described above, it will be necessary to get a clear overview of the current supply chain. The framework should prescribe how managers can analyse and document the necessary information about the current supply chain.

3.1.3 Multiple criteria decision-making

Instead of what most current optimization modelling techniques do, the framework should not be driven by a single objective, e.g. minimising costs (MacCarthy & Atthirawong, 2003). Fahimnia et al. (2013) also emphasized the urgent need for decision supporting systems in supply chain context that embrace multiple criteria. The first step is to identify the criteria that are involved in the decision. Accordingly, these criteria should get different weights according the goals and objectives of the managers (Rezaei, 2016). Finally, indicating variables have to be identified and analysed in order to measure the effects of the decision on the performances on the criteria. More than one variable may be required to measure the performance on each criterion (Macharis, De Witte, & Ampe, 2009). Examples of variables are labour costs, transportation costs, and quality of the labour force. It is not realistic to list all the possible variables since these are very dependent on the process and organization. The framework should therefore provide a basic list of most common decision variables.

3.1.4 Decision-making in a multi-stakeholder environment

Another aspect of the allocation problem is that the decision-making happens in a multi-stakeholder environment. All stakeholders have their own interests in the allocation decision. The stakeholders can be divided into groups whereby each group represents a facility of the organization. The interests of these individual stakeholders or stakeholder groups might be conflicting. In order to find a solution that satisfies the whole organization, the framework should be able to incorporate the objectives of all the stakeholders within the organization. Failing to include these stakeholders increases the chance of unsuccessful implementation of the decision. Taking the stakeholders into account is therefore a crucial aspect of problem solving in a multi-stakeholder environment (Bryson, 2004).

3.1.5 Decision-making in organizations

Many decisions in organizations are made by more than one person. Making decisions in groups, teams, or committees has some benefits compared to individual decision-making. Often a greater number of alternatives are examined, more knowledge and expertise are available to solve the problem, and final decisions are better understood and accepted (Lunenburg, 2011). Not only top-level managers make decisions but employees at every level in an organization participate in decision-making. The framework should therefore facilitate a group decision-making process instead of a decision made by just the top-level managers of an organization. Involving more than one person in the decision-making will introduce multiple subjective observations of the problem. The decision-making process, however, benefits from an objective view of the managers. Steps of the framework should therefore propose activities that are performed in a neutral ‘common language’.

3.1.6 Risks and uncertainty

Decision variables that influence the performance of a supply chain in the manufacturing industry have a dynamic behaviour. This behaviour is difficult to predict, which lead to considerable uncertainty in the allocation decision. Three sources of supply chain uncertainty can be distinguished: supply uncertainty, process uncertainty, and demand uncertainty (Bhatnagar & Sohal, 2005). Supply uncertainty is the result of uncertainty of performance of suppliers. Process uncertainty is caused by unreliability of the in-house production processes. Examples are machine breakdowns or high unavailability of the labour force due to illness. Demand uncertainty arises from fluctuations of customer demand. An updated machine from a competitor or an economic crisis can for example seriously decrease the demand of a product.

In the case of production-process-allocation decisions, most uncertainties are easy to identify but hard to predict. Variables like labour costs, transportation costs, exchange rates, or product demand are known to be dynamic but are hard to predict on the long term. An approach that performs very well in such situations is scenario analysis. A scenario analysis identifies a set of possible futures, each of whose occurrence is plausible. By offering more than one forecast managers are able to make better decisions (Schnaars, 1987). The framework should therefore prescribe how to develop and use scenarios.

3.2 Frameworks, methods, and tools

In literature the words framework, method, and tool are often used in an inconsistent manner. Since the objective of this thesis project is to develop a decision support framework, the definition of a framework should be clear. A framework is defined as a multi-step guideline where each step consists of one or more activities that contribute to the final objective of the framework. The framework can be seen as a food recipe where multiple steps result into a dish. However, instead of making a dish, the objective of this framework is to support decisions about the allocation of production processes. The output of the framework can be used by managers to make these kinds of decisions based on more than just assumptions.

Since the framework is a multi-step guideline, it should prescribe how each step can be performed. The aspects of the allocation problem mentioned in 3.1 can be quite different for every organization. Just as with food recipes, where ingredients can be added or removed depending on your own taste, the framework should offer managers with the freedom to adjust the steps to fit them to their problem. The number of facilities, stakeholders, criteria etc. should therefore not be fixed by the framework.

3.3 Requirements of the decision support framework

Table 1 summarizes the requirements for the framework. The requirements are split in functional, user, and contextual requirements. Functional requirements indicate what the framework should achieve once it is realized. User requirements indicate which requirements should be fulfilled on behave of the future users, in this case the managers. Contextual requirements indicate which constraints have to be considered when applying the framework (Verschuren & Hartog, 2005). The user requirements originate from the case study. The functional and contextual requirements come from literature and emerged during the development of the framework. Each requirement is labelled with a ‘need-to-have’ or ‘nice-to-have’ type of requirement. The eventual framework should at least fulfil the ‘need-to-have’ requirements before the design performs as intended (Dym, Little, Orwin, & Spjut, 2009). Fulfilling the ‘nice-to-have’ requirements strengthens the framework but are not hard requirements for a successful design.

Table 1: Requirements of the decision support framework

Nr.	**Functional requirements**	**Section**	**Type**
1	The framework should prescribe how to analyse the current supply chain in a neutral ‘common language’.	Author*	Need-to-have
2	The framework should prescribe how to identify the stakeholders of the allocation decision.	(Bryson, 2004)	Need-to-have
3	The framework should prescribe how to incorporate goals and objectives of multiple stakeholders.	(Bryson, 2004)	Need-to-have
4	The framework should prescribe how to identify the criteria.	(Bryson, 2004)	Need-to-have
5	The framework should prescribe how to weight the criteria according the goals and objectives of the stakeholders.	(Rezaei, 2016)	Need-to-have
6	The framework should provide a basic list of indicating variables.	Author*	Nice-to-have
7	The framework should prescribe how to develop and use scenarios.	(Schnaars, 1987)	Need-to-have
8	The framework should prescribe how to simulate the performances on the criteria.	Author*	Need-to-have
9	The framework should prescribe how to valuate the performances on the criteria.	Author*	Need-to-have
10	The framework should prescribe how the results of the analysis should be presented in a way that managers can make allocation decisions.	Author*	Need-to-have
Nr.	**User requirements**	**Source**	**Type**
11	The framework should explain each step and activity so it is executable by others.	Case study	Need-to-have
12	Once managers used the framework and made a decision, it should be possible to adjust a few variables without redoing all the steps of the framework. The output (graphs, numbers, etc.) should be automatically updated.	Case study	Need-to-have
Nr.	**Contextual requirements**	**Source**	**Type**
13	The framework should be able to incorporate quantitative criteria and qualitative criteria.	(MacCarthy & Atthirawong, 2003)	Need-to-have
14	The framework should be able to incorporate capacity and capability constraints.	Case study	Need-to-have
15	The framework should be able to handle problems with unlimited facilities and production processes.	Author*	Need-to-have
16	The framework should be able to take into account all the impacts of shifting production processes.	(Fahimnia, Farahani, Marian, & Luong, 2013)	Need-to-have

* Due to the iterative nature of the thesis this requirement emerged during the development of the framework and does not have one specific source.

4. Building the decision support framework

This chapter describes the development of the framework. Existing methods are evaluated, modified, and combined into a decision support framework that fulfils the requirements defined in the previous chapter. The framework, which is the output of this chapter, will be applied in the next chapter to a real case of Dewulf NL.

4.1 The foundation of the framework

Since an important requirement is that it should be possible to make the allocation decision based on multiple criteria, Multi-Criteria Decision Analysis (MCDA) is used as a basis for the framework. Ishizaka and Nemery (2013) described a selection of different MCDA methods and situations where each of them is most suited. Four of these methods, including why the methods are used or not, are described below:

- **Analytic hierarchy process** (AHP)
  AHP is useful when the decision maker is unable to construct a utility function. A utility function is a representation of the perceived utility given the performance on a criterion. An important feature of this method is that the decision maker does not have to assign a numerical score to the performance on the criteria. Instead, the decision is divided in multiple pairwise comparisons where the decision maker can give a relative verbal appreciation. When the construction of the utility function is very difficult or requires a lot of effort, this method might be the best for the decision-making process. However, making pairwise comparisons for many decisions will be consume a lot of time. For the purpose of this framework, which is making decisions about the allocation of lots of production processes at once, this method is therefore not applicable.
- **Analytic network process** (ANP)
  If the decision criteria are dependent, ANP is recommended. For example, when buying a car, the criteria 'engine power' and 'speed' are correlated. If the decision-maker assumes that these criteria are independent, these joint criteria would have heavier weights. For the allocation of production processes the criteria are usually independent (e.g. costs, quality, lead time). ANP is therefore not used because it would make the analysis unnecessarily complicated. However, a lesson learned is that the managers have to define criteria that are independent. For example, if lead time and delivery time are mentioned as separate criteria, these have to be combined into one time-related criterion since these two are highly dependent.
- **Measuring Attractiveness by a Categorical Based Evaluation Technique** (MACBETH)
  MACBETH is a similar method as AHP but evaluates the pairwise comparisons based on an interval scale instead of a ratio scale. MECBETH is not used for the same reason as AHP, namely that it needs a large quantity of information for the pairwise comparisons.
- **Multi-attribute utility theory** (MAUT)
  MAUT is recommended when the utility for each criterion is known. The utility function is not necessarily known at the beginning of the decision process, so the managers need to construct it first. Since the method is based on the principle that the managers' preferences can be represented by a function, it is possible to simulate multiple scenarios, use different criteria weights, and determine alternatives to maximize the utility of a large number of decisions at once. Although the construction of the utility function is a very challenging task, the MAUT is used for this framework. The main reason for this is that it is the best method to allocate a large number of production processes at once.

Another requirement is that the objectives and goals of multiple stakeholders have to be included. Multi-Actor Multi-Criteria Analysis (MAMCA), which is an extension of the traditional MCA, is a method that is able to do this (Macharis, De Witte, & Ampe, 2009). With this method it is possible to compare alternatives according both quantitative and qualitative factors for multi stakeholder problems. The method provides the manager with insight on the differences between de stakeholders and helps to find a solution that satisfies all the stakeholders involved. This information can be used to make the stakeholders more aware of the objectives of the other stakeholders. Furthermore, including all the stakeholders improves the likelihood of acceptance of the solution. The MAMCA method exists of the following seven steps.

1. Define alternatives
2. Stakeholder analysis
3. Define criteria and weights
4. Criteria, indicators and measurements methods
5. Overall analysis and ranking
6. Results
7. Implementation

These steps are used as the foundation of the decision support framework because they fulfil requirements 2, 3, 4, 5, and 6.

4.2 Steps of the decision support framework

This section describes the step-by-step approach of the proposed framework. The developed decision support framework consists of the following ten steps:

Step 1: Define production processes
Step 2: Define facilities
Step 3: Stakeholder analysis
Step 4: Define and analyse influencing variables
Step 5: Develop scenarios
Step 6: Simulate performances on the criteria
Step 7: Valuation of the performances on the criteria
Step 8: Define criteria weights
Step 9: Allocate production processes
Step 10: Decision-making

Step 1: Define production processes

The first two steps define which production processes have to be allocated and among which facilities these processes have to be allocated, in other words, define the alternatives. The first step of the framework is to define which production processes have to be allocated within the organization. The more production processes an organization chooses to review, the more complex the problem becomes. Organizations should consider to include production processes in the analysis if they believe that they can improve the supply chain of their products by shifting these processes. The main driver of organizations to relocate a production processes to another facility is to reduce the production costs. Other drivers can be to open a new market or create more flexibility (Dachs, Ebersberger, Kinkel, & Waser, 2006). An Important driver to offshore production processes (allocating production processes in a foreign country) is the shortage of capacity and skilled labour force in the domestic country (Klinkel & Maloca, 2009). This is for example a problem in the Netherlands, where the employment of skilled labour force in the industry sector is increasingly becoming more difficult (UWV, 2017).

For any reason, it could be possible that certain production processes have to stay together. If so, these processes have to be clustered. For example, if a production process P1 and P2 have to be performed at the same facility they have to be allocated together at the same facility. This has to be defined for all the production processes in the analysis.

Step 2: Define facilities

In this step the organization has to decide which facilities have to be incorporated in the analysis. Again, the more facilities the more complex the problem becomes. To get an overview of the current supply chain of the organization, a supply chain analysis of the organization and the chosen facilities should be performed. The Supply Chain Operations Reference (SCOR) model is recommended because the output serves as a neutral 'common language' (Liepina & Kirikova, 2011). The main reason SCOR is used is because it allows managers to simplify the complex supply chain networks of organizations. The SCOR model is a widely accepted framework related to the supply chain activities of an organization (Supply Chain Council, Incl., 2010). With SCOR, it is possible to evaluated and compare supply chain activities with other organizations, but in this framework it is solely used to evaluate. The analysis consists of an organizational level analysis and a facility level analysis. A Geographical Map and Tread Diagram should be made on organizational level. These two will analyse the relations between the facilities, their suppliers, and customers. Accordingly, the Customer Order Decoupling Point (CODP) for each facility can be defined. The CODP is the point in the supply chain where the product is linked to a specific customer order (Olhager, 2012). Finally, to analyse the supply chain within the facilities, a Business Scope Diagram should be made for the selected facilities. Al these sub-steps are explained below.

Draw a Geographical Map

A Geographical Map visualizes the inbound material flow, outbound material flow, and the material flow between the facilities of the organization. This is done by showing the location of suppliers, facilities, and customers on a map. Arrows between these locations should present the material flow between these locations. The map provides the managers with an insight in the distances between the facilities.

Draw a Thread Diagram

The Geographical Map should be converted into a Thread Diagram. This diagram focuses of the inter-organization processes. Each relation from the Geographical Map should be transformed into arrows with the corresponding labels from table 2.

Table 2: Arrow types

Label	Description
S1	Source make-to-stock products
S2	Source assembly-to-order parts
S3	Source make-to-order products
S4	Source engineer-to-order products
M1	Make-to-stock

M2	Assembly-to-order
M3	Make-to-order
M4	Engineer-to-order
D1	Deliver make-to-stock products
D2	Deliver assembly-to-order products
D2	Deliver made-to-order products
D3	Deliver engineered-to-order products

These arrows show which type of products (make-to stock, assembly-to-order, make-to-order, or engineer-to-order) are supplied by the suppliers and demanded from the customers. Make-to-stock products are products which are made for stock based on demand forecasts, and not actual demand. This type of production can be regarded as push-type production. Customers can order these parts without delivery times besides the normal handling and transportation time. Assembly-to-order products are parts and subassemblies which are finished into a product when customers place an order. Make-to-order products are standard products of a company but these are only made when they are ordered. Engineer-to-order products are products which are specially developed for a customer. The last three types of production can be regarded as pull-type production. Pull-type means that production is based on actual demand (Zenjiro, 2012). By making a distinction between these types of products managers get a better understanding of what kind of production processes are performed at the facilities.

Define the Customer Order Decoupling Point

The type of production mentioned above influence the CODP (see figure 5). The CODP is the last point at which inventory is held. The processes before this point are push-type and processes behind this point are pull-type. These two types of processes are significantly different (Olhager, 2012). When production processes are performed at another facility the CODP might also change. Managers can decide upfront where the CODP will be for or can develop different scenario in step 5 where different CODPs are compared to each other.

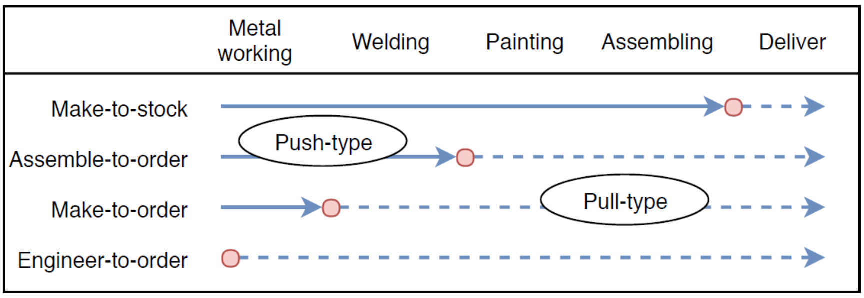


Figure 5: Customer Order Decoupling Point

Draw Business Scope Diagram for each facility

A Business Scope Diagram should be made for each facility which is part of the analysis. The diagram zooms in on each facility in order to map the material and information flow between the different departments within the facility. This provides the managers with the current practices of the facilities.

Step 3: Stakeholder analysis

As mentioned in the introduction, the problem of allocating production processes within an organization is a multi-stakeholder problem. To increase the chance of successful implementation of the decision a stakeholder analysis should be performed. For this problem there will be multiple stakeholders for each facility that is included in the analysis. It is also possible that there are stakeholders outside the facilities that have to be included because their participation is necessary to assure successful implementation (Bryson, 2004).

The first thing to do is to identify who the stakeholders are. Reed, et al. (2009) described three methods for identifying stakeholders: Focus groups, Semi-structured interviews, and Snowball sampling.

- **Focus groups**
  During a focus group a small group brainstorms about potential stakeholders, their interests, influence, and other attributes.
- **Semi structured interviews (supplement to focus group)**
  Interviews with a cross-section of stakeholders to check focus group data
- **Snowball sampling**
  Snowball sampling is a technique where initial stakeholders are interviewed and asked for new stakeholders until all stakeholder are identified.

In this framework, the stakeholders are employees with decision-making power within the organization. Thus, the stakeholders are selected from a definite set of people, and the identification is rather simple compared to for example big infrastructure projects. Therefore, Snowball sampling is used for the identification of stakeholders because it is the easiest and fastest method. This technique entails that one stakeholder at each facility is asked to suggest other stakeholders who should also be incorporated in the analysis. This is repeated until the stakeholders do not suggest any new stakeholders, or the managers believe that there are enough stakeholders involved to provide a representation of each facility. Eventually this will result in a list of stakeholders for each facility (Reed, et al., 2009).

Next, the goals and objectives of these stakeholders should be identified. Eventually, the goals and objectives will be used as decision criteria. The identification of criteria should be done for each stakeholder to reduce the chance that criteria are missing. Defining the importance of the criteria is not included in this step. This will be done in step 6. Bryson (2004) described multiple stakeholder analysing techniques from which two are discussed below.

- **Power versus interest grid**
  A power versus interest grid is a powerful method to map the power dynamics of the stakeholders. All the stakeholders are placed on a grid that expresses their power and interest in the decision.
- **Interviews or group sessions**
  During interviews or group sessions, the stakeholders are asked to list the criteria they would use to judge the production process allocation. Furthermore, they are asked which constraints have to be taken into account when making allocation decisions.

During the case study it appear that a power versus interest grid does not add any value to the decision-making process. This tool is better applicable when one wants to analyse a decision-making process instead of facilitating a decision-making process. The goals and objectives of the stakeholders should therefore be identified by interviews or group sessions. The interviews or group sessions should start with open questions to discover the objectives and goals of the stakeholders. After that, more directed questions could be asked to reveal whether the stakeholders pursue other objectives or goals they did not mention yet. Examples of questions that can be asked during the interviews are:

Open questions

- What are, according to you, the strengths of the organization?
- Which strengths of the organizations are important to maintain when allocating the production processes?
- What are problems you currently face in your daily work related to the production processes?
- What should, according to you, be improved with allocating the production processes?
- What are constraints which have to be considered when allocating production processes?

Directed questions

- Is lead time a criterion which should be considered when allocating the production processes?
- Is the gained inventory space at a facility an objective or goal when allocating the production processes?
- Is it important to consider the maximum capacity of the facilities?

Depending on the number of stakeholders and the variety of criteria, one could choose to make stakeholder groups. These groups can be based on the facility or on the departments where the stakeholders are working. Keeping these group separate in the analysis will show where the stakeholders differ in objectives and how this influences the allocation choice.

Step 4: Define and analyse influencing variables

The first activity of this step is to define the variables that influence the performance on the criteria. A list of basic variables that are of relevance for most manufacturing organizations is shown in table 3. This table is the result of a literature study to important variables to consider when allocating production processes. The variables are found in literature on methods to locate new production facilities, supply chain efficiency, make-or-buy decisions, manufacturing success, drivers to outsource production processes, drivers to offshore production processes, but also drivers to re-shore production processes. The latter one it is especially interesting because it reveals some common mistakes made by organizations in the past to offshore production processes. The last column summarizes the variables mentioned by the stakeholders in the case study.

Table 3: List of influencing variables

Variables	**Source**								
Facility dependent variables	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**	**[9]**
Fixed costs	X			X	X	X	X	X	X
Transportation costs	X	X	X	X	X	X	X	X	X
Labour costs	X	X	X	X	X	X	X	X	X
Labour efficiency	X			X				X	
Availability of labour force	X	X	X		X				X
Quality of the labour force	X		X	X	X	X	X		X
Quality of suppliers	X								
Quality of transportation modes	X		X						
Availability of space for future expansion	X								
Availability of storage space		X			X				
Machines and equipment		X	X						X
Shipping pattern			X						X
Focus on core business				X					
Lead time					X				X
Environmental uncertainty						X		X	
Manufacturing flexibility						X	X		
Infrastructure	X							X	
Proximity to the market / suppliers	X	X							
Process dependent variables	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**	**[9]**
Innovativeness and complexity								X	
Amounts per year			X		X			X	X
Costs of side activities								X	X
Process time			X						X
Product dimensions									X
Type of components needed			X						X

[1] (MacCarthy & Atthirawong, 2003)
[2] (Alvarez, 2007)
[3] (Prasad & Sounderpandian, 2003)
[4] (Visser, 2000).
[5] (Dale & Cunningham, 1984)
[6] (Swamidass & Newell, 1987)
[7] (Roth & Miller, 1992)
[8] (Snoo, 2016)
[9] Case study Dewulf

Overall, it can be concluded that, even though most authors say that there are more variables to consider than just costs, most attention in literature is paid to cost-related variables. The set of variables from the table can be seen as a basic set that is relevant for all production processes (metal working, welding, assembling, painting) of manufacturers in all industries (agriculture, automotive, earthmoving etc.). However, dependent on the case, there might be some additional process- or industry-specific-variables.

Only variables that are identified, and for which is enough data available to analyse them can be included in the analysis (known knowns). Sometimes variables are identified but cannot be analysed due to a lack of data or because they are too much time consuming to analyse (known unknowns). Moreover, there might also exist other variables which should influence the decision because they are relevant but are not even identified (unknown unknowns). The analysis is simplified from reality due to only including the known knowns in the analysis. When managers make decisions based on the results of the analysis they have to know which variables are included and which not. For that reason all the assumptions made during the analysis have to be well documented.

The next activity is to connect the variables to the criteria. The performance on the criteria is often influenced by multiple variables (Macharis, De Witte, & Ampe, 2009). It is also possible that certain variables influence the performance on multiple criteria. To get a clear overview of these relations, it is useful to visualize the connections between the variables and criteria. Making a figure with lines between the variables and criteria increases the awareness of the impact of the factors and simplifies the overall analysis in the next step.

The final activity is to actually analyse the influencing variables. Two categories of variables can be distinguished: facility-related variables and production-process-related variables. The facility-related variables have to be analysed for each facility that is part of the analysis. The production-process-related variables have to be analysed for each production process that has to be allocated to one of the facilities. Depending on the variable, various methods and tools can be used to analyse them. For some variables this can be more difficult than for others. Cost-related variables can for example simply be summed up, but quality-related variables have to be judged by the managers themselves or independent experts.

Step 5: Develop scenarios

Scenario analysis is a forecasting method that is based on a more qualitative and contextual description of how the present will evolve into the future, rather than using complex quantitative models. It turned out that scenario analysis is usually equally accurate as these more time consuming complex models. Besides using some results of quantitative models as input, scenario analysis proceeds more from the gut than from the computer. It suggests to consider a number of plausible assumptions, rather than a single one that may later turn out to be incorrect. Another advantage of scenario analysis is that by incorporating multiple values for the variables, the assumptions made during the analysis in step 4 become less consequential (Schnaars, 1987).

With scenario analysis, a set of possible futures is identified and evaluated. For this framework it entails that some of the values of the variables analysed in step 4 take another value. These changes can be based on trends, expectations, or just curiosity. Ideally, 3-5 future scenarios should be created and analysed (Amer, Daim, & Jetter, 2013).

For this framework a deductive approach to create scenarios is most suitable. That is, first selecting a dominant background for each scenario (e.g. increased demand or economic expansion in Eastern Europe), and then forecast each of the key variables in light of each of these themes. The advantage of this approach is that the variables can be combined into a set of consistent scenarios that capture the general theme. In some applications, there is a single dominant variable whose value is central to the theme (e.g. labour costs to economic expansion in Eastern Europe). However, in most business applications there is more than a single unknown. Usually 3-8 uncertain variables should be considered for each scenario.

The created scenarios should be documented so they can be used in the step 7. If preferable, managers can array the scenarios in order of probability of occurrence. However, avoid assigning probabilities to the scenarios. Such probabilities convey a sense of precision that is not there. Scenarios are possibilities, not probabilities.

Step 6: Simulate performances on the criteria

The next step is to simulate all the production processes at the selected facilities. Simulation is a powerful tool to perform analysis of complex problems. Simulation can play an important role in decision-making in supply chain management. It is especially useful for testing and comparing different scenarios (Terzi & Cavalieri, 2004). Four simulation types can be distinguished:

1. Spreadsheet simulation
2. System dynamics
3. Discrete-event dynamic systems simulation
4. Business games

The simplest type of simulation is a spreadsheet simulation. For the purpose of this framework the spreadsheet simulation offers enough possibilities. The other three types of simulation require much more time and often specializes software tools. A spreadsheet simulation can be made in Microsoft Excel, which is already available at nearly all manufacturing organizations. Within the spreadsheet, the performances on the criteria of all the production processes should be simulated. This should be done for all the scenarios. The performance on the criteria might be influenced solely by facility-related variables. In that case, the performances will be the same for all the production processes. Other performances might be influenced by facility- and production-process-related variables. In that case, the performances can be different for the production processes. Simulated performances can be quantitative and qualitative. Quantitative performances (e.g. costs) should be calculated. Depending on the criteria, qualitative performances might need pictures, short stories, or other descriptive explanations based on the relevant influencing variables in order to be valuated in the next step.

Step 7: Valuation of the performance on the criteria

Comparing and ranking alternatives (facilities in this case) on multiple criteria is an often discussed but also criticised exercise. The performance on the criteria should be normalized into a common language in order to make a comparison based on multiple criteria. With a common language is meant that the valuation of the performance on the criteria proceeds consistent and that the grades have an absolute meaning. Without a common language, there can be no consistent collective decision-making. Different applications call for different common languages. However, it is not clear how to define a common language. Existing common languages (e.g. judging gymnastics, or figure ice skating) developed through many experimentations over a long time (Balinski & Laraki, 2007).

The purpose of this step is to assign a score to each production process at each facility based on the performance on the criteria (hereinafter called performance scores). A common language for this activity does not yet exist. This thesis proposes a grading system of 1 till 10 for the valuation of both quantitative and qualitative performances. During the case study this grading system appeared to be easily understandable and provide reliable results. A scale of 1 till 10 was easily understandable because all the managers of the case study are Dutch and have used this grading system since primary school. When applying the framework on a case with managers from other nationalities, they might experience more difficulties with this scale and prefer to use another grading system. For example, a scale of -3 till 12 for Danish managers, a scale of 1 till 6 (where 1 is the lowest and 6 the highest score) for Polish managers, or a scale of 1 till 6 (where 1 is the highest and 6 the lowest score) for German managers. Because the performance scores have to be multiplied by the criteria weights obtained in the next step, only numerical scales will work. For example, the five-point letter system (A,B,C,D and E/F) used by many universities in the United States cannot be used unless it will be converted into a numerical scale. Independent from which grading system will be used, it is important that all the quantitative and qualitative performance scores are judged with the same grading system. Figure 6 shows the valuation ranges of the quantitative and qualitative performance scores for the 1 till 10 grading system used in this thesis.

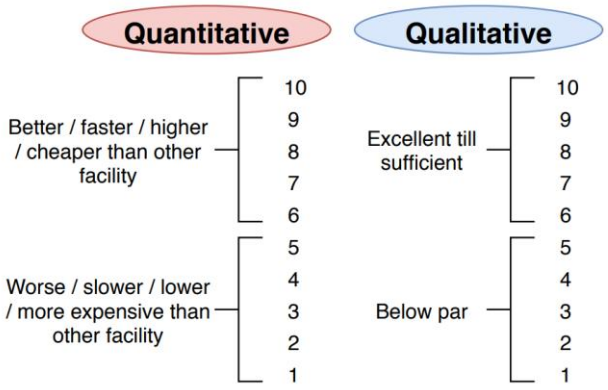


Figure 6: Valuation ranges of quantitative and qualitative performance scores

Qualitative performances have to be judged by independent experts. Quantitative performances have to be judged based on numerical variables. Managers have to realize that for any grading system they use, they are making the assumption that the difference of one point in one criterion is the same as the difference of one point at another criterion, which is in reality not the case. Anyhow, this assumption has to be made in order to continue with the analysis. To minimize the deviation of reality managers should use frequency tables of the chosen grading system to determine which score to assign to the quantitative performances. A frequency table states how much percent each grade is assigned within the grading system. By using this table, the performance scores are brought on the same level as the qualitative performances judged by experts. Only than, they can be compared to each other. Some alternatives of frequency tables that can be used for the Dutch 1 till 10 grading systems are shown below.

Table 4: Alternatives of frequency tables for a 1 till 10 judgment scale (Dutch grading system)

Dutch university		Alternative 1		Alternative 2		Alternative 3	
Score	%	Score	%	Score	%	Score	%
10	0,8%	10	0,4%	10	0,4%	10	10,0%
9	5,8%	9	2,9%	9	2,9%	9	10,0%
8	26,6%	8	13,3%	8	13,3%	8	10,0%
7	35,7%	7	17,9%	7	17,9%	7	10,0%
6	31,0%	6	15,5%	6	15,5%	6	10,0%
5	0%	5	15,5%	5	50,0%	5	10,0%
4	0%	4	17,9%	4	0,0%	4	10,0%
3	0%	3	13,3%	3	0,0%	3	10,0%
2	0%	2	2,9%	2	0,0%	2	10,0%
1	0%	1	0,4%	1	0,0%	1	10,0%

Alternatives 1 and 2 are based on the grades that students received on their graduation project at a Dutch university, which are shown on the left side of the table 4 (Radboud University, 2017). Students only received sufficient grades (6 till 10), since grades lower than a 6 result in a fail and students have to redo their graduation project or quit their study. However, for this framework a scale from 1 till 10 is required. The grades of the Dutch university are transformed in two ways. Both ways are transformed such that 50% of the scores are between 6 and 10 and the other 50% of the scores are between 1 and 5. This is because performances on quantitative criteria, e.g. costs, are expressed as relative values compared to the other facility (see figure 6), which entails that 50% will be cheaper than the other facility and 50% will be more expensive than the other facility.

For alternative 1, the frequencies are mirrored at 5.5 and divided by two (in order to make the total 100%). For alternative 2, the same frequencies are used for sufficient grades (6 till 10), but the last 50% is assigned with a score of 5. The recommended alternative is alternative 1 because if certain processes are much more expensive it seems logical that they receive a lower score than processes that are just a little bit more expensive than the other facility.

If a reliable frequency table is not available, alternative 3 should be used. In this alternative a 10 is assigned to the first 10% best, fastest, or cheapest performances, a 9 to the second 10%, and so on until a 1 to the worst, slowest, and most expensive 10% performances. This alternative is preferred over normalizing the performances based on just the maximum and minimum values because the results will be less sensitive to adding or removing production processes from the decision. The results are very sensitive to adding or removing production processes from the decision if the scores are normalized based on the highest and lowest value. Unfortunately, neither of the alternatives described above is scientifically proven to be a sound method to compare quantitative and qualitative performances. The recommendation is based on trial and error during the case study.

Step 8: Define criteria weights

The criteria of the stakeholders, which are investigated in step 3, are not all of the same importance. The importance highly depends on each individual organization (Alvarez, 2007). Moreover, the stakeholders can mutually assign different weights to the criteria. For example, stakeholders in planning departments might be more focused on lead time than other stakeholders. To get an overview of the differences, each stakeholder must assign weights to the criteria according to the importance they attach to it. It is important that the stakeholders all perceive the criteria in the same way. In other words, the stakeholders must exactly know which variables determine the valuation of the performance on the criteria. The figure with the variables and criteria relations made in step 4 is helpful for this activity.

Accordingly, the criteria weights of the stakeholders can be investigated. Many methods for criteria weighting exist. Examples are Entropy, CRITIC, MOORE, SAW (Vujičić, Papić, & Blagojević, 2017), and a more recent developed method, the Best-Worst Method (BWM). The BWM is used in the framework to assign weights to the criteria. The main reason why the BWM is used is because it can easily be performed in a digital questionnaire and send around. This is particularly useful when one needs to deal with stakeholders among different facilities in different countries. Additionally, the BWM provides a consistency ratio to check the reliability of the comparison (Rezaei, 2016). This reliability check is useful because the lack of consistency for pairwise comparisons can be a significant challenge (Rezaei, 2015). The BWM consists of four steps, which are explained below.

BWM Step 1: Determine the most and the least important criteria

In this step the stakeholders are asked to identify which is, in their opinion, the most important criterion and least important criterion to consider when allocating production processes within the organization.

BWM Step 2: Determine the preference of the most important criterion over all the other criteria

Stakeholders are asked to compare the most important criterion to the other criteria. They have to assign a score from 1 to 9 to each criterion whereby 1 is equally important as the most important criterion and 9 is extremely more important than the most important criterion. This results in a best-to-others vector. The resulting vector can be written as:

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$$

BWM Step 3: Determine the preference of all the criteria over the least important criterion

The same is done for comparison of all the criteria over the least important criterion. The stakeholders again assign a score from 1 to 9 to each criterion whereby 1 is equally important as the least important criterion and 9 is extremely more important than the least important criterion. This results in an others-to-worst vector. The resulting vector can be written as:

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T$$

BWM Step 4: Find the optimal weights

In this step the goal is to determine the weights of the objectives such that the maximum absolute differences $\left|\frac{W_B}{W} - a_B\right|$ and $\left|\frac{W_B}{W} - a_B\right|$ for all factors are close as possible to zero. The model which can be derived from this is:

$$\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi \text{, for all j}$$

$$\left|\frac{w_B}{w_W} - a_{jW}\right| \leq \xi \text{, for all j}$$

$$\sum_j W = 1$$

$$W_j \geq 0\text{, for all j}$$

Solving this model will find the optimal weights and ξ. With ξ and the consistency index table (table 5), the consistency ratio can be calculated by:

$$Consistancy\ ratio\ = \frac{\xi}{consistancy\ index}$$

A consistency ratio close to zero shows a high consistency of the stakeholders. There is not a threshold of this value before the answers of a stakeholder are unreliable. If a stakeholder shows a much higher consistency ration than the other stakeholders it should be considered to ask the respondent to revise his or her answers.

Table 5: Consistency index table

Number of criteria	1	2	3	4	5	6	7	8	9
Consistency index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

The BWM should be performed for each stakeholder. If the stakeholders are separated in groups, the average criteria weights of those stakeholders per group should be used in the next step. At first sight, it seemed logical to perform the BWM right after defining the criteria (step 3). However, during the case study it appeared that it is useful to first list the influencing variables so that stakeholders know on which variables the performances on the criteria are based.

The final activity of this step is to validate the criteria weights. This is required because in practice the stakeholders may not pursue the criteria they mentioned during the interviews. For the validation the criteria should be compared with the key performance indicators (KPI) of the stakeholders. KPI are variables that are used to measure the performance of an organization, a project, or an individual employee. If stakeholders assign high criteria weights to criteria which do not match their KPI's, further questioning to the criteria is required.

Step 9: Allocate production processes

The next step is to allocate the production processes in such a way that the criteria of the stakeholders are maximally satisfied. In this thesis the word 'allocate' is used. However, in some cases it might be 'relocating' production processes because these processes are currently performed in a certain facility and moved to another facility. Nevertheless, the word 'allocate' is used because in this step the processes are virtually pulled out of the organization and allocated to one of the facilities (not depending on where they were performed before the analysis). To do so, the performance scores should be multiplied with the corresponding criteria weights obtained in step 8. When the stakeholders are divided into stakeholder groups, the groups should be kept apart. Next, the production processes should be allocated in such a way that the sum of total weighted performance scores is maximal. Many optimization tools are able to do this but Opensolver is recommended. Opensolver is an open source software tool which can be used as an add-in in Microsoft Excel. It solves linear and integer problems without putting a limit on the size of the problem. This step should be repeated for each scenario developed in step 5. The results of the scenarios should be kept apart. So eventually, each scenario will result in a solution for each stakeholder group.

Step 10: Decision-making

The final step is to make a decision about the allocation problem. The results of step 9 should be presented in such a way that the managers can use the information to make the allocation decision. During the case study it appeared that this step is required since the result of steps 9 (a big list of allocations per stakeholder per scenario) did not provide managers with useful information for the decision-making. Decision-making about the allocation of production processes is divided into long-term and short-term. The characteristics of both types are shown in table 6.

Table 6: Short-term and long-term decisions characteristics (Jones, Atkinson, Lorenz, & Harris, 2012)

Short-term decision	**Long-term decisions**
Tactical in nature	Strategic in nature
Meeting short-term goals	Impact on corporate level objectives
Decisions involve relatively small financial investments	Decisions involve large financial investments
Relatively easy to change the decision	Wrong decisions can have a major financial impact on the organization

For making long term decisions (e.g. recruiting new welders or buying new welding robots), managers benefit from seeing the big picture. For these kinds of decisions, the distribution of all the processes among the facilities should be shown. Based on a percentage of total process time, managers can make decisions where to hire more employees or invest in welding robots. However, the results of the analysis in step 7 do not necessary have to be all in the same direction. The different criteria weights of the stakeholders and the different scenarios can suggest conflicting allocations. If so, the causes should be identified. These causes can start the discussion between the managers in order to find a solution. A cause of conflict can for example be that the weights of stakeholder groups are conflicting, these stakeholder groups should than start the discussion and find an appropriate solution that satisfies both stakeholder groups. Another cause can be that the different scenarios suggest conflicting allocations. In this case the managers could determine the most optimistic and the most pessimistic scenario. Based on those two they can decide whether the costs of the most pessimistic scenario weigh up against the possible results of the optimistic scenario. If not, the manager should adjust the investments plans until they do.

For making short-term decisions (e.g. where to perform a new production process), managers benefit from a simple tool that they can use to make fast decisions based on the results of the analysis. For short-term decisions, the managers have to choose one scenario and one set of criteria weights on which he or she wants to base the decision. The most obvious scenario to use in this case is the current state of the variables, since the variables are not likely to change a lot within this short period. A simple decision tool should be developed where managers have to insert the production-process-related variables (think of process time, product dimensions, etc.), and accordingly the tool should suggest at which facility this process should be performed.

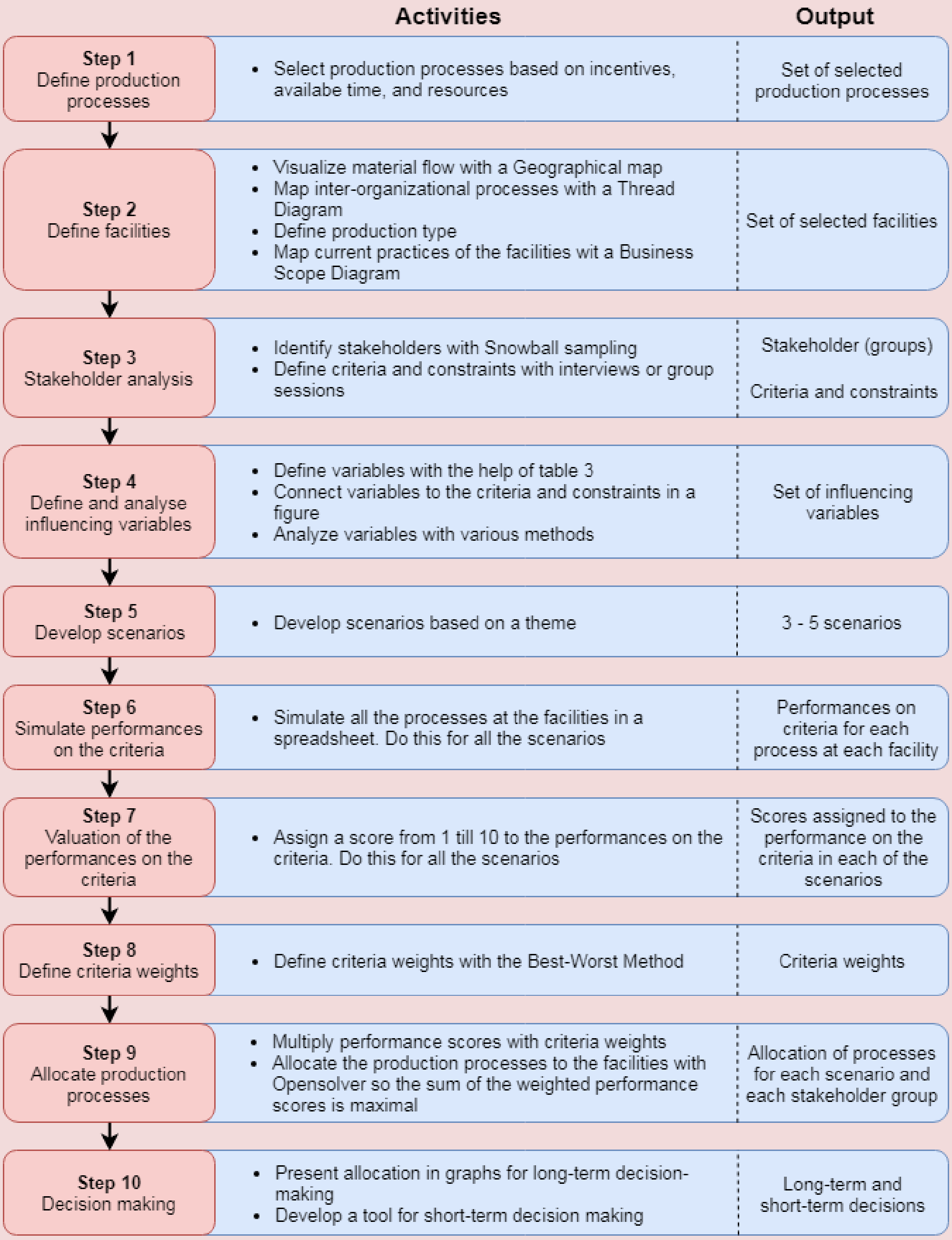
Graphs and tools for both long- and short-term decisions should be presented within the same spreadsheet as step 6 and 7. Updating any variable will then automatically adjust the data according the updated situation.

4.3 Summary of the decision support framework

The previous section, which explained the development of the ten steps, is the conceptual design of the framework. This section describes the detailed design of the framework. A manual of how to use the framework is shown in boxes on the next pages. The manual is made in such a way that it can be presented on a webpage or in a flyer.

Decision support framework for the allocation of production processes

This framework supports the decision-making of the allocation of production process within machinery manufacturing organizations. The framework consists of ten steps which are shown in the figure below.



	Activities	Output
Step 1 Define production processes	• Select production processes based on incentives, availabe time, and resources	Set of selected production processes
Step 2 Define facilities	• Visualize material flow with a Geographical map • Map inter-organizational processes with a Thread Diagram • Define production type • Map current practices of the facilities wit a Business Scope Diagram	Set of selected facilities
Step 3 Stakeholder analysis	• Identify stakeholders with Snowball sampling • Define criteria and constraints with interviews or group sessions	Stakeholder (groups) Criteria and constraints
Step 4 Define and analyse influencing variables	• Define variables with the help of table 3 • Connect variables to the criteria and constraints in a figure • Analyze variables with various methods	Set of influencing variables
Step 5 Develop scenarios	• Develop scenarios based on a theme	3 - 5 scenarios
Step 6 Simulate performances on the criteria	• Simulate all the processes at the facilities in a spreadsheet. Do this for all the scenarios	Performances on criteria for each process at each facility
Step 7 Valuation of the performances on the criteria	• Assign a score from 1 till 10 to the performances on the criteria. Do this for all the scenarios	Scores assigned to the performance on the criteria in each of the scenarios
Step 8 Define criteria weights	• Define criteria weights with the Best-Worst Method	Criteria weights
Step 9 Allocate production processes	• Multiply performance scores with criteria weights • Allocate the production processes to the facilities with Opensolver so the sum of the weighted performance scores is maximal	Allocation of processes for each scenario and each stakeholder group
Step 10 Decision making	• Present allocation in graphs for long-term decision-making • Develop a tool for short-term decision making	Long-term and short-term decisions

Figure 7: The decision support framework

It is recommended to perform the steps in this order. Managers might decide to iteratively enrich the results by first performing the analysis with a lower number of variables, and accordingly increase the number of variables in order to increase the precision of the analysis. It is highly recommended to perform the steps of the framework in a spreadsheet. A template can be downloaded at: https://bitly.com/2JV1viQ (see appendix A).

Step 1: Define production processes
Select the production processes that have to be allocated among the facilities of the organization. List these processes in the first sheet of the template. Each production process will be allocated to just one facility. If certain production processes have to stay together at the same facility, these have to be clustered (e.g. if production process P1 is allocated at facility F1, then production process P2 also have to be performed at facility F1). Clustering can be done by assigning the same number to it in the cluster column in the first sheet.

Step 2: Define facilities
Select the facilities that are potential locations to perform the production processes. List the facilities in the second sheet of the template. Draw a Geographical Map and a Thread Diagram to get an overview of the current supply chain. Then, define the current Customer Order Decoupling Point and find out whether this point will move when the production processes are allocated differently. If so, determine the effects of it on the delivery time of the product, flexibility of the production, etc. This will be used later on in step 7. Next, draw a Business Scope Diagram for each selected facility to get an insight in the capabilities of the facilities.

Step 3: Stakeholder analysis
To identify the stakeholders, start asking the plant manager of each facility to suggest other stakeholders who should also be involved in the decision-making process. In turn, ask those stakeholders to suggest other stakeholders until no new stakeholders are suggested. Depending on the number of stakeholders, one might decide to make stakeholder groups. Next, the criteria on which the analysis will be made should be determined. This should be done by one-by-one interviewing the stakeholders or organizing a group session. In the beginning of the interviews or group sessions open questions should be asked about which objectives and goals the stakeholders want to peruse when allocating the production processes among the selected facilities. Accordingly, more directed questions should be asked to reveal whether stakeholders pursue other objectives or goals they did not mention yet. Note that both quantitative and qualitative criteria are possible. Besides objectives and goals, also important constraints should be identified during the stakeholder interviews or group sessions.

Step 4: Define and analyse influencing variables
The next step is to identify the variables that influence the performance on the criteria. These are production-process-related variables (process time, product dimensions etc.) and facility-related variables (labour costs, quality, transportation costs etc.). List all the production-process-related variables in the first sheet of the template behind the production processes and all the facility-related variables in second sheet. Table 3 of the thesis helps with the identification of influencing variables.

Step 5: Develop scenarios
Develop 3-5 scenarios of possible futures. Base these scenarios on a certain theme (e.g. economic expansion or an economic crisis). For each scenario, change the value of 3-8 uncertain variables based on the theme. Place the values of the scenarios in the scenario columns at the first two sheets of the template.

Step 6: Simulate performances on the criteria
Use the spreadsheet to simulate the performances on the criteria of each production process at each facility. Do this for all the scenarios. The performance of criteria might be influenced solely by facility-related variables. In that case, the performances will be the same for all the production processes. Other performances might be influenced by facility- and production-process-related variables. In that case, the performances can be different for the production processes. Simulated performances can be quantitative and qualitative. Quantitative performances (e.g. costs) should be calculated. Depending on the criteria, qualitative performances might need pictures, short stories, or other descriptive explanations based on the relevant influencing variables in order to be judged in the next step. Use a separate sheet for each facility to simulate the performances.

Step 7: Valuation of the performances on the criteria
In this step, a score should be assigned to the performance on each criterion. This should be done for all the production process. The valuation of the performances can be divided into two types: the valuation of performances on qualitative and quantitative criteria. Have qualitative performances (e.g. quality or flexibility) judged by independent experts. Let them assign a score from 1 till 10 to the performance on the criteria for all the facilities*. For quantitative performances (e.g. costs), calculate the differences between the facilities and assign a score to the performances based on the following intervals.

Score	Assign to
10	0,4%
9	2,9%
8	13,3%
7	17,9%
6	15,5%
5	15,5%
4	17,9%
3	13,3%
2	2,9%
1	0,4%

The best 0,4% performances should be assigned with a 10, the following best 2,9% with a 9, and so on, until the last 0,4% which should be assigned with a 1.

** if the grading system of 1 till 10 is not common for the experts and mangers, then consult the thesis for another valuation method.*

Step 8: Define criteria weights
Use the Best-Worst Method to define the weights for the criteria. Consult the thesis to see how to perform the Best-Worst Method. Perform the Best-Worst Method individually for each stakeholder. If stakeholder groups are made in step 3, calculate the average criteria weights of those stakeholders.

Step 9: Allocate production processes

In this step the production processes should be allocated to the selected facilities so that the criteria of the stakeholders are maximally satisfied. This allocation might be different for each scenario and each stakeholder perspective. First, multiply the performance scores with the corresponding criteria weights. Next, use Opensolver to allocate the processes to the facility at which it satisfies the stakeholders the most. Opensolver is free available as a spreadsheet add-in. Opensolver should be programmed as follows:

- Select one of the facilities by assigning a 1 to it. The other facilities should be assigned with a 0.
- If the facility is assigned with a 1, use the weighted performance scores of that facility. If the facility is assigned a 0 do not use the weighted performance scores.
- If due to a constraint it is not possible to select a facility, remove that facility from the alternatives for that production process.
- If a production process is clustered to other processes, the other processes should be allocated at the same facility.
- Maximize the sum of the weighted performance scores.

Perform this step for each scenario and for each stakeholder perspective on a separate sheet in the template.

Step 10: Decision-making

In the final step decisions about the allocation of production processes should be made. Two types of decisions are distinguished, long-term and short-term. For long-term decision-making, the allocations of the previous step should be presented in graphs. Graphs should be made for each scenario, each including the perspective of all the stakeholders. Different graphs for production processes with certain characteristics can be made to see which processes should be allocated to which facilities (e.g. transport dimensions). Based on these graphs, managers can make decisions about long-term investments. For short-term decision-making, a simple tool should be developed. The tool, which should also be made within the spreadsheet, should suggest a facility based on some production-process related questions (e.g. how big is the product or how long is the process time). The tool should choose the facility at which the criteria of the stakeholders are most satisfied. The average of the criteria weights of all the stakeholders and the current scenario should be used for short-term decision-making.

4.4 Verification of the requirements

To verify that the design of the framework performs as intended, it is checked whether the initial stated requirements are fulfilled. Table 7 shows which requirements are fulfilled, partly fulfilled, or open for improvement, and indicates in which step they are fulfilled. The requirements that are partly fulfilled or up for improvement are discussed below the table.

Table 7: Verification of the requirements

Nr.	Requirement	Fulfilled	Partly fulfilled	Open for improvement	In step
	The framework should prescribe...				
1	how to analyse the current supply chain in a neutral 'common language'.	☑	☐	☐	2
2	how to identify the stakeholders of the allocation decision.	☑	☐	☐	3
3	how to incorporate goals and objectives of multiple stakeholders.	☑	☐	☐	3
4	how to identify the criteria.	☑	☐	☐	3
5	how to weight the criteria according the goals and objectives of the stakeholders.	☑	☐	☐	8
7	how to develop and use scenarios.	☑	☐	☐	5
8	how to simulate the performances on the criteria.	☑	☐	☐	6
9	how to valuate the performances on the criteria.	☑	☐	☑	7
10	how the results of the analysis should be presented in a way that managers can make allocation decisions.	☑	☐	☐	10
	The framework should...				
11	explain each step and activity so it is executable by others.	☐	☑	☑	-
6	provide a basic list of indicating variables.	☑	☐	☐	4
13	be able to incorporate quantitative criteria and qualitative criteria.	☑	☐	☐	-
14	be able to incorporate capacity and capability constraints.	☑	☐	☐	-
15	be able to handle problems with unlimited facilities and production processes.	☑	☐	☐	-
16	be able to take into account all the impacts of shifting production processes.	☑	☐	☐	-
	Once managers used the framework and made a decision...				-
12	it should be possible to adjust a few variables without redoing all the steps of the framework. The output (graphs, numbers, etc.) should be automatically updated	☑	☐	☐	-

Most requirements of the framework are fulfilled. Two requirements are open for improvement. The first, how to valuate the performances on the criteria, which is probably the most challenging step of the framework, is open for improvement because it is uncertain whether the chosen valuation method is the most suitable method for the purpose of this framework. There is not sufficient literature available on this topic of decision-making to be able to compare and select the best valuation method. The second, explain each step and activity so it is executable by others, is open for improvement because with the current detailed design managers are probably not able to perform the analysis without any help of the author. To improve this point a specialized computer program could be made. This would, however, decrease the possibilities for managers to adjust steps to make them more suitable for their problem, which was the initial reason it is chosen to develop a framework instead of a method.

5. Case study: Allocation of welding processes of Dewulf NL

In this chapter the framework is applied to the case of Dewulf NL. First, a description of the case is provided. Second, the allocation problem of the organization is elaborated. Third, the steps of the decision support framework are executed. Finally, conclusions and recommendations are drawn for the organization.

5.1 Case description

The organization used for the case study is the Dewulf-group. Both the organization and the agricultural machinery industry they are operating in are described.

5.1.1 The organization

Dewulf-group is an agricultural machinery manufacturer specialised in the production of machines involved in producing potatoes and other open-field vegetables. The company initially started with the production of agricultural machines in Belgium. In 2008, Dewulf opened a new production site in Romania with the aim to achieve greater manufacturing efficiencies and costs savings. One year later a second production site in Belgium was opened. In 2014, Dewulf took over Miedema, a Dutch agricultural machinery manufacturer. With this cooperation the organization offers a complete product range for potato production. This made the Dewulf-group become one of world's leading companies in the agricultural machinery industry (Dewulf, 2014). Examples of machines they produce are shown in figure 8 and 9.

Figure 8: Dewulf's potato planting machine

Figure 9: Dewulf's potato harvesting machine

Currently, the Dewulf-group exists of the four following facilities:

- Winsum, Netherlands: Dewulf NL (Before Miedema)
- Roeselare, Belgium: Dewulf BE
- Roeselare, Belgium: Dewulf DMC
- Braşov, Romania: Dewulf RO

Thanks to the acquisition of Miedema, Dewulf NL has new possibilities in the supply chain of their products. The facility now has more options to allocate their production processes within the organization. This new situation might enable a more efficient supply chain for facility and/or the organization. Currently, Dewulf NL does not have a structured method to decide about how to allocate their production processes. Due to this, uncertainties arise about what production processes they have to perform in the future.

The production processes of Dewulf NL are a perfect case to investigate how the supply chain of a facility and/or organization can be improved by reviewing the allocation of production processes. The main reason for this is that the organization has production sites in different countries, so different circumstances, but also because the situation is rather new, which increases the chance of improvement.

The main problem for the Dewulf NL is that there is uncertainty about how to allocate welding processes within the organization. They can either keep performing all welding processes at Dewulf NL, move all processes to Dewulf RO, or move some processes to Dewulf RO. If some processes are moved, which processes should be moved to Dewulf RO and which stay at Dewulf NL? The framework developed in this thesis will help to solve this problem. Furthermore, the production facilities can use the output of the framework to optimize their production processes. As an example, Dewulf NL does currently not know how to optimize their welding processes or warehouse inventory management because they are uncertain about what future production processes they have to perform in this facility. Although the latter mentioned problems are not within the scope of this thesis project, Dewulf NL can use the results of this thesis in their attempt to optimize these processes.

5.1.2 The agricultural machinery industry

The Dewulf-group is a manufacturer in the agricultural machinery industry. This industry is characterized by high seasonal fluctuation in demand. In Europe, the demand of potato planting machines is much higher in February and March than in August and September. For harvesting potato harvesting machines this is the opposite. The industry is also characterized by an increasing trend in customer specific solutions. This leads to a high variety of options on agricultural machines. The machines are often made-to-order. Dewulf NL aims at a delivery time of six weeks for standard machines. Performance and reliability is more important than the aesthetics for agricultural machinery but since bad-looking machines might represent a bad-working machine aesthetics cannot be ignored.

5.2 The production process allocation problem of Dewulf NL

The problem of Dewulf NL is that they are uncertain about whether they should offshore their welding processes to the facility in Romania (Dewulf RO). One of the reasons why this problem only arises for their welding processes is that in the past few years it became more difficult to find skilled welders for these processes in the Netherlands (UWV, 2017). For the production facility in Romania this is less of a problem and additionally they offer much lower labour costs. It therefore seems reasonable to investigate the opportunities of moving some, or all welding processes to Dewulf RO. Moving some, or all of the welding processes will have great impact on the current supply chain of the organization. This potential shift is illustrated in figure 10.

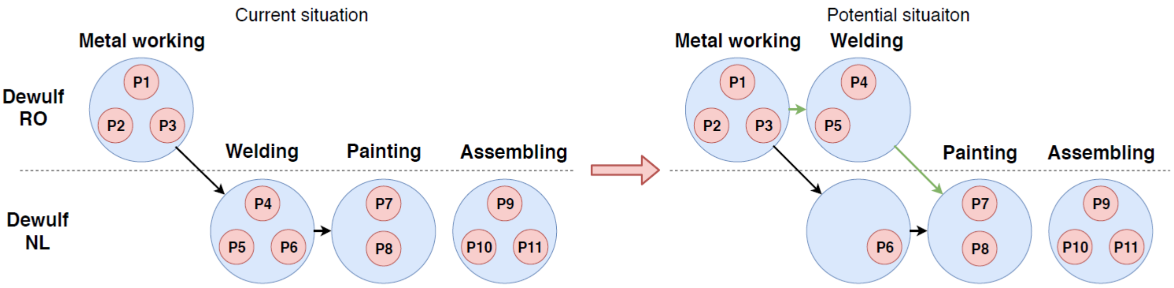


Figure 10: Potential shift in the supply chain

Making this decision will lead to new questions like: how to transport the welded (sub) assemblies and where to source the parts required for these assemblies? This, together with the other effects of moving some or all welding processes have to be investigated before being able to make the decision. Dewulf NL chooses to include all welding processes because they are wondering if they can utilize the possibilities of a facility in a low wage country and because finding skilled labour for these processes is becoming more difficult in the Netherlands. Two examples of assemblies which are welded are shown in figure 11 and 12.

Figure 11: Example assembly: Frame 10103510

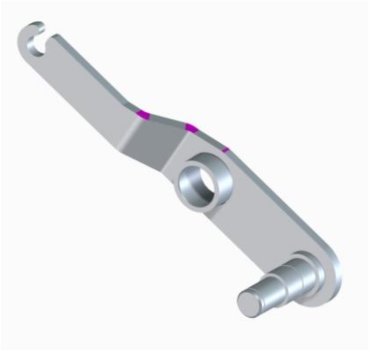


Figure 12: Example assembly: Tensioner 10500270

As visible in the figures, the assemblies can widely differ in size and complexity. Also, the amount per year can widely differ between the assemblies.

5.3 Appling the framework on the production process allocation problem of Dewulf NL

This section applies the ten steps of the decision support framework to the case of Dewulf NL. due to confidentiality reasons some data is removed from this public version.

5.3.1 Step 1: Define production processes

All welding processes which are currently performed in the facility in the Netherlands are included in the analysis. The welding processes of 2017 are used for the analysis because these provide the most recent information about the production processes of Dewulf NL. Information about the welding processes is retracted from the database of Dewulf NL. Both manual and robot welding processes are included. Dewulf NL performed about 19.000 welding activities having a total process time of more than 17.000 hours in 2017. In this case a welding activity is defined as a single welding order of an assembly which can be repeated multiple times per year. The total number of unique assemblies in 2017 was 2.000. Since these 2.000 assemblies have to be distributed among the facilities these are called the production processes. It is assumed that one production process is either performed at Dewulf NL or Dewulf RO. This assumption seems reasonable because the efficiency of production processes will increase if a process is performed more often at the same location due to learning and economies of scale. Besides, welding jigs are needed for many welding processes. Making the same jig at both facilities is something that should be prevented.

5.3.2 Step 2: Define facilities

As mentioned, Dewulf NL and Dewulf RO are the facilities that are included in the analysis. The current supply chain of the organization and both facilities is analysed and shown in the sections below.

5.3.2.1 Analysis of the Dewulf-group

A geographical overview of the organization is shown in figure 13.

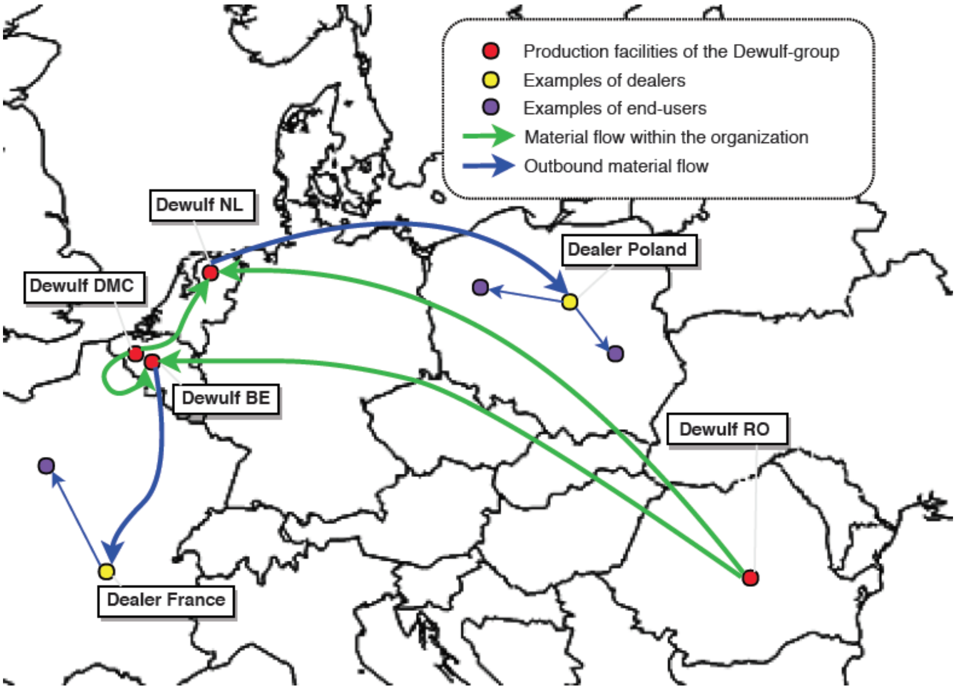


Figure 13: Geographical map of the Dewulf-group

The products produced at Dewulf RO are transported to Dewulf NL and Dewulf BE by an external Romanian transportation company. Usually, trucks arrive two times per week (Tuesday and Friday) at the facilities in Western Europe. When possible, freights to Dewulf NL and Dewulf BE are combined in one truck. In this case the truck first visits Dewulf BE, then picks up parts from Dewulf DMC produced for Dewulf NL before driving to the Dutch facility. It is also possible that freights are removed when there are not sufficient orders to ship or freights are added when there is not enough capacity to transfer all the orders in one truck.

Just two example dealers are included because there are too many to capture them all in one map. The dealers of the Dewulf-group, which are spread all over the world, can be seen as the customers of the organization. Dewulf NL and Dewulf BE deliver machines to these dealers. The Dewulf-group has approximately 123 dealers in 41 countries. End-users of the products are customers of the dealers. The Tread Diagram of the organization is shown in figure 14.

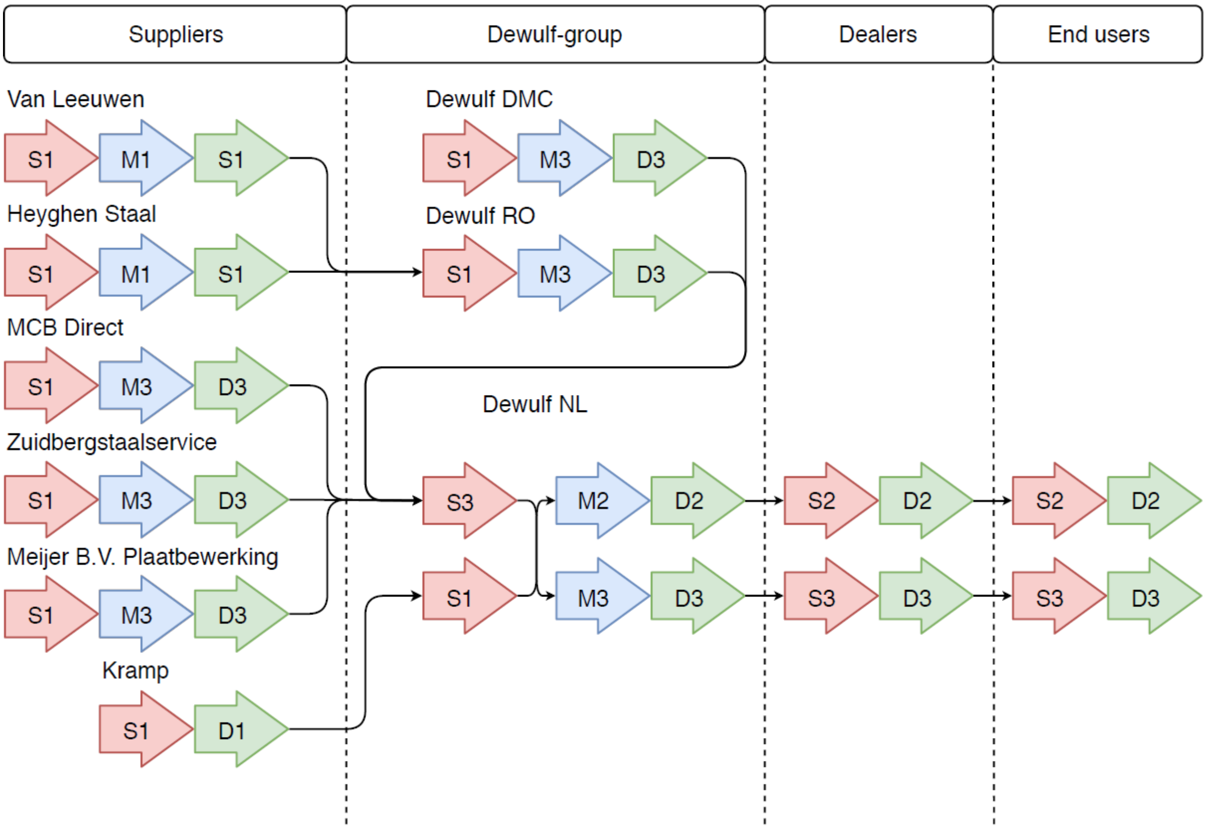


Figure 14: Tread Diagram Dewulf-group

To keep the diagram clear, only main suppliers which are relevant for the welding processes of Dewulf NL are included in the Thread Diagram. Regarding to the welding processes, the production at Dewulf NL is currently mainly 'assemble-to-order'. Often used components for the welding processes are laser cut plates, beams cut or laser cut on length, and machined shafts delivered by some Dutch suppliers, Dewulf RO or Dewulf DMC. Components needed for the welding processes are often on stock at Dewulf NL where they get welded when an order comes in. Due to this Dewulf NL can ensure short lead times.

When welding processes are allocated at Dewulf RO instead of Dewulf NL, the CODP the production might change to 'make-to-order'. This depends on whether the stock of the components will also be held at Dewulf RO. In either case, the production will become a little bit more pull-type. This will have both advantages and disadvantages. Lead times of the products will increase due to the transportation time but the flexibility of the production will increase since it will become easier to recover faults in laser cut plates.

5.3.2.2 Analysis of Dewulf NL

Business Scope Diagrams are made for the individual facilities. Figure 15 givens an overview of the production processes of Dewulf NL. Only departments related to the welding processes are included in the diagram. The lead time that is reserved for each process is indicated by a number of working days in the red circles. The process is described below the figure.

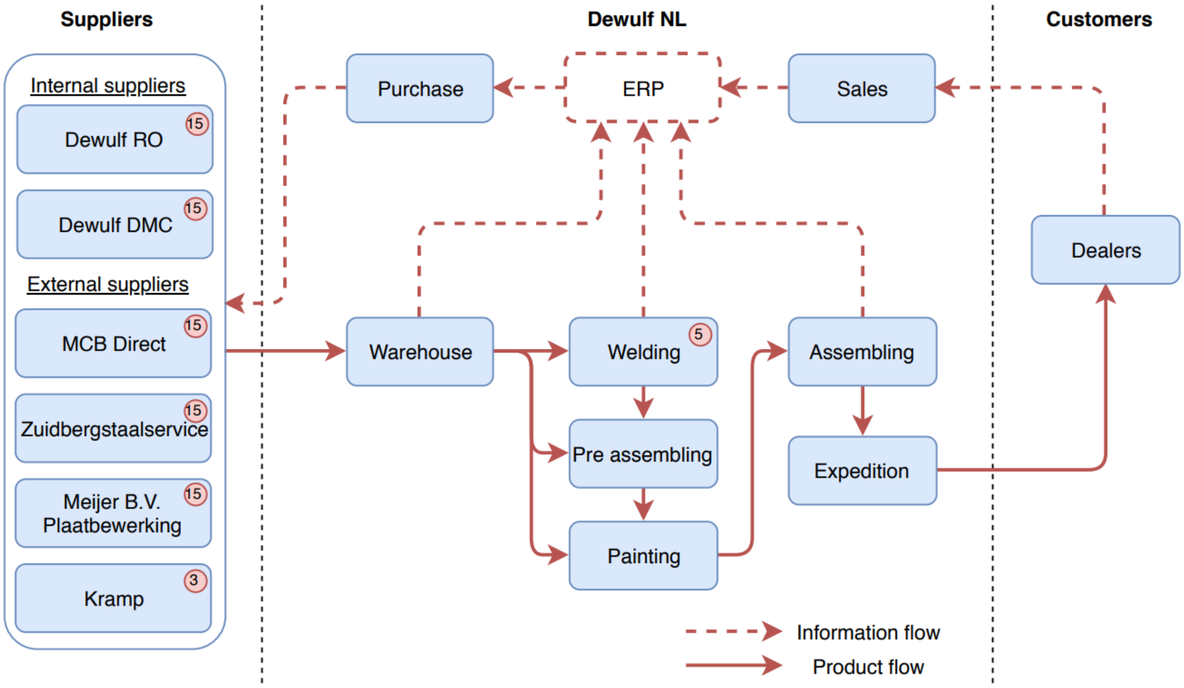


Figure 15: Business Scope Diagram Dewulf NL

Dealers all over the world sell machines of Dewulf NL. The sales department processes these sales and create a demand in the ERP system. The ERP knows which components are on stock and which components need to be ordered. Accordingly, the purchase department orders parts required to fulfil the demand from the suppliers. In this case, only components which need to be welded are relevant to analyse. MCB Direct, Zuidbergstaalservice, Meijer B.V. Plaatbwerking, Dewulf DMC, and Dewulf RO are the most used suppliers for these components. An average delivery time of fifteen days is reserved for these suppliers. When the parts arrive, they are put into the warehouse. Order pickers collect the right parts from the warehouse and bring these to the welding area where the assemblies are welded manually or by a welding robot. Dewulf NL has two welding robots with a maximum length of two meters, one welding robot with a maximum length of five meters, and about twenty manual welders. For some assemblies a welding jig is made to decrease the process time, increase quality, or to make the process possible for the welding robot. After welding, the parts can be pre-assembled before going to the painting area or go directly to the painting area. After painting, the parts are assembled into machines which go to the expedition and will be delivered to the dealers by a transportation company.

5.3.2.3 Analysis of Dewulf RO

Just as for the facility in the Netherlands, a Business Scope Diagram is made for Dewulf RO (see figure 16). All processes are discussed below the figure. The lead time that is reserved for each process is indicated by a number of working days in the red circles.

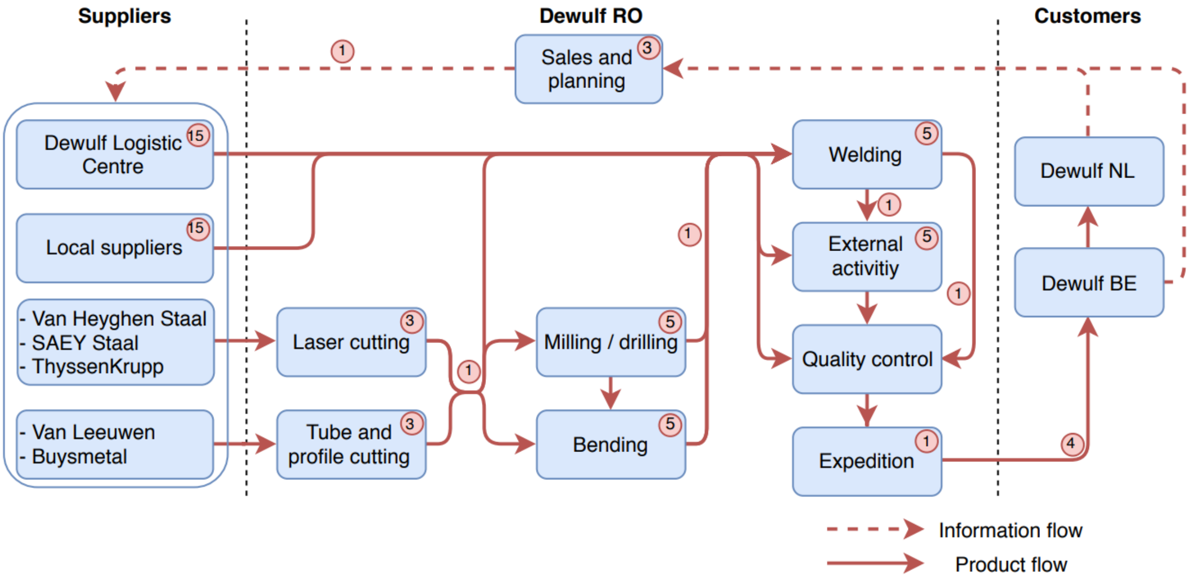


Figure 16: Business Scope Diagram Dewulf RO

The flow starts with an order of Dewulf BE or Dewulf NL. The sales and planning departments process these orders. Raw materials and parts that are required to fulfil the orders are ordered at multiple suppliers. The main suppliers of Dewulf RO are the suppliers of steel plates, tubes, and profiles. These components are ordered on stock so the supply of them does not affect the lead time. Van Heyghen Staal, SAEY Staal, Van Leeuwen, and Buysmetal are located in Belgium. ThyssenKrupp is located in Romania. Furthermore, there are some other local suppliers who deliver make-to-stock and make-to-engineer parts. Since the company initially started in Belgium, there are still suppliers from Belgium who supply products which are needed during the welding processes at Dewulf RO. These products are collected at Dewulf's Logistics Centre in Roeselare and shipped to Dewulf RO when they order it.

The production processes at Dewulf RO start with metal working. Steel plates are laser cut by one of the two laser cutting machines. The maximum dimension that the laser can cut is 3,00m x 1,50m with a maximum thickness of 20mm. Tubes and profiles are cut on length by a band saw machine. It is possible to order all kinds of tubes and profiles if there is a certain demand for it. Then there is the option to mill or drill the parts. This is done by a CNC milling machine. It is also possible to bend steel plates. There are three press brakes with a length of 2,2m, 3,2m, and 4,2m. The maximum plate thickness that can be folded on the 4,2m press brake is 6mm (full length). The next possibility is to weld the parts into assemblies. This can be done by a welding robot or manual welders. The decision to perform a welding process on the welding robot or manually is based on quantity, complexity, and desired quality. These decisions are made during production meetings. The welding robot, which has five working stations, is rather new and thus at the beginning of its learning curve. The efficiency of the robot is therefore much lower than the welding robots at Dewulf NL. Manual welding is done by seventeen welders. Six of them are welding bigger constructions that do not fit on a welding table. Eleven of them are welding smaller assemblies in welding boxes.

The welded assemblies and laser-cut parts can be galvanized or powder coated at a local supplier. After that, all parts have to pass the quality control before going to the expedition. At the expedition the products are packed for transport or stored in the warehouse until they will be shipped.

5.3.3 Step 3: Stakeholder analysis

The stakeholders with decision-making power are identified by Snowball sampling. In this case the stakeholders are divided into three stakeholder groups. Each stakeholder group represents a facility of the Dewulf-group.

Table 8: Stakeholder of the Dewulf-group

Stakeholders at Dewulf NL		Stakeholders at Dewulf RO		Stakeholders at Dewulf BE	
Name	**Function**	**Name**	**Function**	**Name**	**Function**
Removed from the public version					

The criteria that are mentioned by the stakeholders are costs, quality, lead time, and solving seasonal fluctuations at the facilities (hereinafter called ‘season’). With the ‘season’ criterion is meant that the stakeholders aim to an equal occupation of the facilities through the whole year. The constraints which were mentioned were all capacity- or capability-related constraints.

5.3.4 Step 4: Define and analyse influencing variables

Figure 17 shows which variables are used to judge the performance on the criteria. The figure shows how the variables are connected to the criteria and constraints. Table 3 is used to identify the influencing variables. Besides the variables from table 3, some additional industry-specific variables are mentioned by the stakeholders. Only the variables that are identified and analysable with the available data are used in the analysis (known knowns). The variables are elaborated below the figure

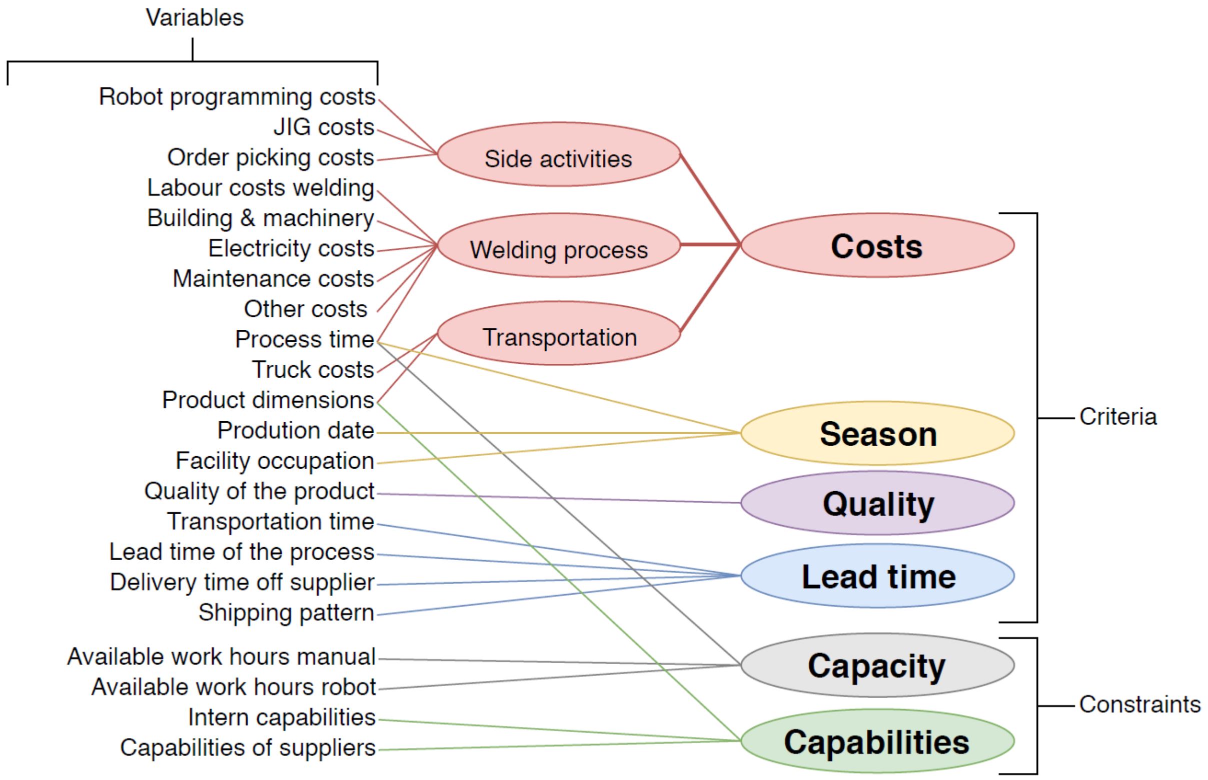


Figure 17: Relationships of variables, criteria, and constraints

For each variable the analysing method is explained, assumptions which are made for the analysis are elaborated, and the results of the analysis are presented*. The production process dependent factors are measured by investigating the welding processes which are performed at Dewulf NL during 2017. The facility dependent factors are investigated by visiting both facilities.

Robot programming costs and jig costs

Since robot programs and welding jigs already exist for all the assemblies that are welded in 2017, these costs are not included in analysis of the production processes of 2017. However, the costs of writing robot programmes and developing jigs will be included in the tool for short-term decision-making. If a new robot program has to be written, or a jig has to be made, it is assumed that the costs depend on the labour costs, number of components, and the robot welding time.

	Dewulf RO	Dewulf NL
Labour costs robot programmer (€/hour)	Removed from the public version	
Programming time		
Robot welding time		
Labour costs jig developer (€/hour)		

Jig development time	Removed from the public version
Number of components	
Labour costs jig maker (€/hour)	
Jig making time	

Order picking costs

The order picker costs are calculated by multiplying the order picking time with the order picker labour costs. The order picking time is different for each assembly. It is assumed that the order picking time depends on the number of components of the assembly.

	Dewulf RO	**Dewulf NL**
Labour costs order picking (€/hour)	Removed from the public version	
Order picking time		
Number of components		

Labour costs welding, fixed facility costs, electricity costs, overhead costs, ...

For all the costs related to the welding processes, a full costs price is used for both facilities. This cost captures the labour costs, overhead costs, fixed costs of machines, fixed costs of the company, electricity costs, depreciations, etc. For Dewulf RO, a full costs price for manual and robot welding is available. For Dewulf NL just one price is known for both manual and robot welding.

	Dewulf RO	**Dewulf NL**
Full costs manual welding (€/hour)	Removed from the public version	
Full costs robot welding (€/hour)		

Total process time

The process times of the welding processes is retracted from the database of Dewulf NL. It is assumed that the process time will be the same at Dewulf RO. To calculate the total costs of each production process per year, the process time is multiplied by the amount per year. There is made a distinction between manual process time and robot process time.

In the database of Dewulf NL, the welding time of the robot is the actual welding time of robot, so this value does not include setup time or time needed to fix and remove the parts in the welding jig. Since the robot hour price that is known for both facilities is based on manual working hours, the actual welding time of the robot is transformed into manual working hours by multiplying it with 1,8.

All assemblies with a processing time of 0 minutes are removed from the analyses. These assemblies are often small assemblies that are welded in bigger assemblies. By removing these assemblies from the analysis, it is assumed that all underlying assemblies of big assemblies are welded in the same facility as the big assembly.

	Dewulf RO	**Dewulf NL**
Process time manual	Removed from the public version	
Process time robot		
Robot welding time		
Amount per year		

Truck costs and product dimensions

The transportation costs for each production process are calculated by:

$$Transportation\ costs = \frac{truck\ costs}{truck\ volume * filling\ efficiency} * \ assembly\ volume * amount\ per\ year.$$

To calculate the transportation volume for each assembly, the maximum length, width, and height of the underlying components is multiplied. This assumption is made because the database of Dewulf NL does not provide the dimensions of the assemblies itself. When taking a few samples, this method appeared to be often correct. Suspicious assemblies (assemblies with a very big volume) are manually checked and adjusted when needed.

	Dewulf RO	**Dewulf NL**
Truck costs	Removed from the public version	
Truck volume		
Filling efficiency		
Max dimensions underlying components		
Amount per year		

Production date and facility occupation

The production date of each production process is retracted from the database of Dewulf NL. For each process, it is expressed how many percent of the total amount was produced in each month in 2017. The results are translated into a graph showing the total welding time per month for all the assemblies (see figure 18).

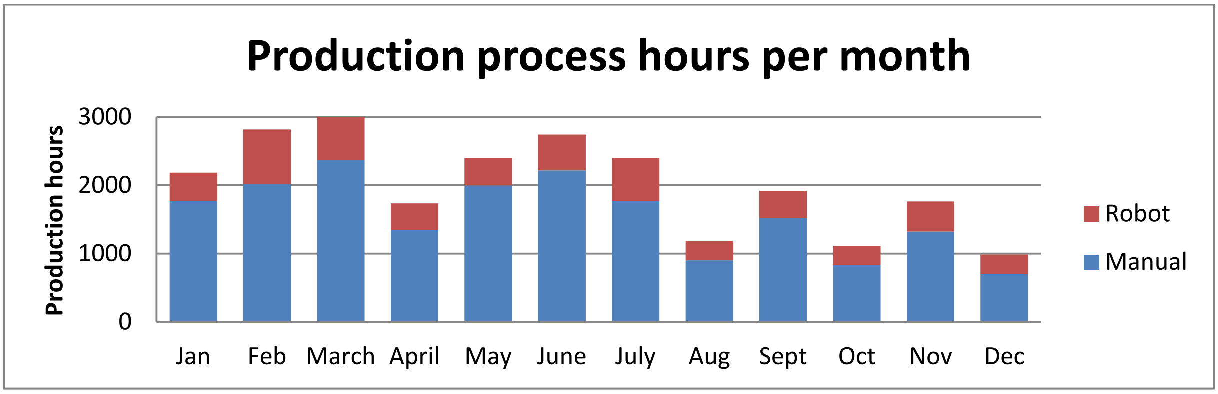


Figure 18: Production process hours per month

Since all these products are currently produced at Dewulf NL, the data also represents the facility occupation of Dewulf NL. To compare the facility occupation of both facilities, the manual and robot welding hours per month are summed up and normalized to a score between 1 and 10. Data about the facility occupation of Dewulf RO is not available. Therefore, the plant manager of Dewulf RO was asked to assign a score from 1 till 10 to each month where 1 is the highest occupation and 10 is the lowest occupation of the year. The results are shown in the graph below.

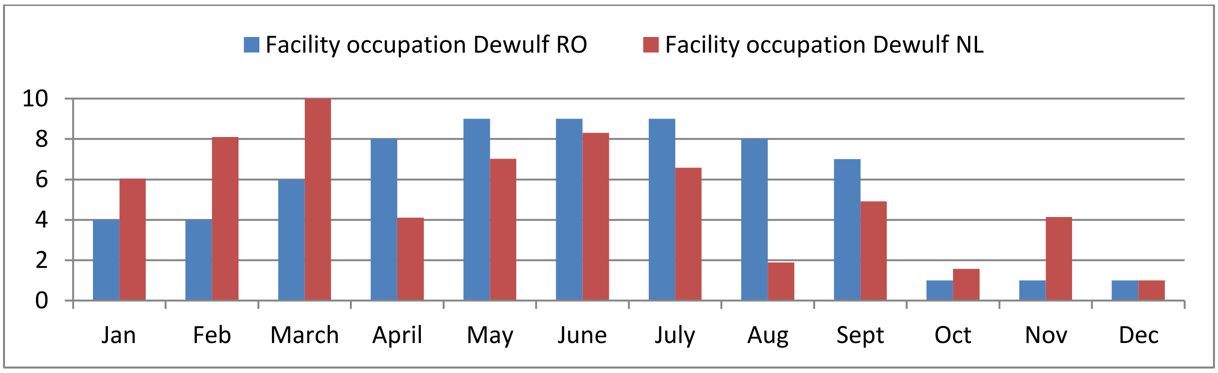


Figure 19: Facility occupation Dewulf RO and Dewulf NL

	Dewulf RO	Dewulf NL
Production date	Removed from the public version	
Facility occupation		

Quality of the labour force

The quality of the product for both facilities is determined by asking an independent welding expert to judge manual weldments. The expert judged 100 randomly made pictures of manual weldments. 50 of these pictures are made at Dewulf RO and 50 pictures are made at Dewulf NL. The expert assigned a score from 1 till 10 to the weldments based on what he could see on the pictures. The quality score therefore solely represents the aesthetics of the weldments, not whether the assemblies have the correct dimensions according to the drawings. The quality of the labour force for both facilities is determined by the average score of the expert. The quality score will only be used for assemblies that are manually welded. The quality for robot welded assemblies is assumed to be equal for both facilities.

	Dewulf RO	Dewulf NL
Quality of the labour force for manual welding	Removed from the public version	
Quality of the labour force for robot welding		

Transportation time, shipping pattern, lead time of the process, and delivery time of suppliers

For both facilities, the transportation time, shipping pattern, lead time of the process, and the delivery time of suppliers is shown.

	Dewulf RO	Dewulf NL
Transportation time	Removed from the public version	
Shipping pattern		
Average lead time of a welding process		
Delivery time of suppliers		

Available manual and robot welding hours

To determine the available manual and robot welding hours, the number of welders is multiplied by the working hours per year for each facility.

	Dewulf RO	Dewulf NL
Working hours per day	Removed from the public version	
Working days per year		
Employees manual welding		

Employees robot welding	
Effective working time	

Intern capabilities and capabilities of suppliers

Since the Dutch suppliers currently do not have any capability restrictions, only the capabilities of Dewulf RO and its suppliers are included in the analysis. The maximum plate dimensions within the assemblies are restricted by the characteristics of the laser and press brake machines. Furthermore, when an assembly is bigger than the dimensions of a truck, it will not be possible to transport it to Dewulf NL.

	Dewulf RO	Dewulf NL
Maximum laser plate dimensions (mm)	Removed from the public version	
Maximum bending dimensions (mm)		
Transport dimensions (mm)		

Known unknowns

Besides the factors that are analysed, there are also factors identified that cannot be analysed due to a lack of data or it is too difficult to analyse them (known unknowns). A list of the known unknowns, including the reason why they are not included in the analysis, is shown in table 8.

Table 9: Known unknowns

Factor	Reason why not included
Back-office costs	This cost is neglected because it is too difficult to define which costs are made for each production process and this cost is probably too low to make a difference in the analysis.
Material costs	Since steel plates and tubes at Dewulf RO are supplied by Belgium suppliers, it is assumed that the costs are approximately the same for both facilities. The transportation costs of steel plates and tubes to Dewulf RO is not included in the analysis.
Labour efficiency	It is assumed that the labour efficiency is equal for both facilities. In other words, the process time is assumed to be equal for both facilities.
Transportation costs of components	Many components are already manufactured at Dewulf RO. Currently, these components are shipped from Dewulf RO to Dewulf NL. When an assembly is welded at Dewulf RO instead of Dewulf NL, the shipment costs of these components will be replaced by the shipment costs of the assembly. So actual transportation costs might be a little bit lower than the values used in the analysis. However, since many components are currently supplied by suppliers from western Europe, transportation costs for these components might be higher when welding at Dewulf RO. In the analysis it is assumed that these differences balance each other.

5.3.5 Step 5: Develop scenarios

Four scenarios are developed. Each scenario is based upon a dominant background.

Scenario 1: Current situation

The first scenario uses the current variable values. This scenario is especially useful for short-term decision-making. Besides, is serves as a basis from which the other scenarios will differ.

Scenario 2: Economic expansion in Eastern Europe

Eastern Europe's economy is growing faster than most countries in Western Europe. Especially in Romania, which was the fastest growing economy of the EU in 2017. Also, the labour costs recorded the biggest growth in the EU with an increase of about 14% compared to 2% on EU average (Mihaylov, 2018). In this scenario it is assumed that this trend continues for the following 5 years. The labour costs are included in the full costs of both facilities. To calculate the full costs in 5 years, only the labour costs part of the full costs is increased with this trend. In this scenario the full costs are calculated with the following formula:

$$Full\ costs\ scenario\ 2 = current\ full\ costs - labour\ costs + labour\ costs * (1 + r)^5$$

It is assumed that economic expansion will also increase the transportation costs.

	Current value		Scenario value	
	Dewulf RO	**Dewulf NL**	**Dewulf RO**	**Dewulf NL**
Full costs manual welding (€/hour)	Removed from the public version			
Full cost robot welding (€/hour)				
Order picking costs (€/hour)				
Transportation costs (€)				

Scenario 3: Shortage of skilled labour force in the Netherlands

It is getting more difficult to contract skilled labour in the Netherlands. In this scenario it is assumed that the labour costs in the Netherlands of welders will increase due to the scarcity of skilled employment. Moreover, the number of welders is decreased, which decreases the available working hours at the Dutch facility. It is assumed that instead of 17 welders just 10 welders are available at Dewulf NL.

	Current value		Scenario value	
	Dewulf RO	**Dewulf NL**	**Dewulf RO**	**Dewulf NL**
Full costs manual welding (€/hour)	Removed from the public version			
Full cost robot welding (€/hour)				
Order picking costs (€/hour)				
Available working hours manual				

Scenario 4: Investments and improvements at Dewulf RO

The last scenario is based on curiosity what will happen to the allocation suggestions if some investments are made at Dewulf RO. The current limits of the laser and the press brake machines will be increased. Another point at which Dewulf RO can improve is the efficiency of the welding robot. Currently the robot is working 40% of the time. This scenario assumes that the working time will be 75%, which decreases the full costs of robot welding.

	Current value		Scenario value	
	Dewulf RO	**Dewulf NL**	**Dewulf RO**	**Dewulf NL**
Maximum length laser (mm)	Removed from the public version			
Maximum length press brake (mm)				
Full cost robot welding (€/hour)				

5.3.6 Step 6: Simulate performances on the criteria

The performances on the four criteria are simulated for both facilities in each of the scenarios. The performances on the criteria ‘costs’ and ‘season’ can be determined by values whereas ‘quality’ and ‘lead time’ have to be described based on the variables. How each performance is simulated is discussed below.

Costs

The performance on the ‘costs’ criterion is determined by summing up all the cost-related variables for each production process. This results into a cost for each production process for both facilities. Accordingly, the cost differences between the facilities are calculated. So, the performance on the ‘costs’ criterion is expressed by how much more or how much less it costs to perform the production process at that facility compared to the other facility.

Season

The performance on the ‘season’ criterion is determined by the following vector calculation:

$$[A\ B\ C\ D\ E\ F\ G\ H\ I\ J\ KL] * \begin{bmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \\ 11 \\ 12 \end{bmatrix} = Season\ score$$

A till L is the production date vector of each production process. ‘A’ values how much percent of the process is performed in January, ‘B’ values how much percent of the process is performed in February, and so on. 1 till 12 is the facility occupation vector of the facility. 1 values the facility occupation score of the facility in January, 2 in February, and so on.

Quality

The quality is solely determined by the expert who judged the randomly taken pictures of weldments from both facilities. The performance of the ‘quality’ criterion is therefore the same as the average value the expert assigned to it. This performances is only used for manual welding. For robot processes the same score for both facilities will be used since the robot quality is equal at both facilities.

Lead time

Since most of the components are on stock at Dewulf NL, it is assumed that the delivery time of suppliers does not affect the lead time. In this case the only difference in lead time is the transportation time of the assemblies. When the assemblies are welded at Dewulf NL this transportation time will be 0 days. When the assemblies are welded at Dewulf RO the transportation time will be approximately 5 days (with incorporating the shipping pattern). The performance on the lead time will be the same for all the production processes.

Besides the four criteria, there are also capacity and capability constraints that influence the allocation decision. Both constraints are elaborated.

Capacity

Whether a facility has enough capacity to perform the production processes is based on the available working hours and the process time of the processes. This constraint is only simulated in scenario 3, where due to scarcity of skilled workforce in the Netherlands less welders are available. For the other scenarios it is not be realistic to include this constraint because at Dewulf NL there is of course enough capacity (since they currently perform the welding processes) and at Dewulf RO there is not any capacity (since they currently are not planning to perform the processes). When managers decide to move welding processes to Romania, Dewulf RO has to contract more and Dewulf NL can contract less welders.

Capabilities

Whether it is possible to perform a production process at Dewulf RO is based on the intern capabilities and the product dimensions. When the assemblies have underlying components, which exceed the limits of the laser or the press brake machines, that assembly is assigned to Dewulf NL. Furthermore, when the assembly dimensions exceed the limits of a truck it is also assigned to Dewulf NL.

5.3.7 Step 7: Valuation of the performances on the criteria

In this step, scores are assigned to the performances on the four criteria for Dewulf NL and Dewulf RO for each production process. The common language that is used is a numerical grading from 1 till 10 because this scale is best understandable by Dutch and Belgium habitants for whom this framework is executed. In this grading system, scores from 1 till 5 are below par and scores from 6 till 10 are sufficient. The judgment of the performances on the four criteria is discussed below and the results are summarized in table 10.

Costs

The performances on the ‘costs’ criterion are divided into 10 equally big categories. The first category (score 10), entails the highest 10% cost savings compared to the other facility, the second category (score 9), entails the second highest 10% cost savings compared to the other facility, etc. until the last category (score 1). The set of costs savings will entail as much negative as positive numbers because for each production process one facility will have positive cost savings and the other will have negative cost savings compared to each other. Due to this, for each production process a score from the first five categories (score 10 till 6) will be assigned to the facility with the lowest costs and a score from the last five categories (score 5 till 1) will be assigned to the facility with the highest costs.

Season

The score on the performance on the ‘season’ criterion is the same value as the simulated performance. A score between 6 and 10 will reduce the seasonal fluctuations and a score between 1 and 5 will increase the seasonal fluctuations.

Quality

The expert also used a numerical scale from 1 till 10 where scores from 1 till 5 are below par and scores from 6 till 10 are sufficient. Therefore, the score of this expert is used also used as the score for the performance score on the criteria. The score is used for all manual production processes. For robot welding the highest possible score is assigned to both facilities since quality for robot welding is the same.

Lead time

The lead time is judged with a score between 1 and 10 where 1 is a very long lead time and 10 is as fast as possible. The judgment is done by the author according the lead times of both facilities. The scores are shown below.

Table 10: Performance scores on the criteria

	Dewulf RO	Dewulf NL
Costs (production process dependent)	Removed from the public version	
Season (production process dependent)		
Quality manual welding processes		
Quality robot welding processes		
Lead time		

It is important to note that in reality, even though much effort is put in the valuation of the performance on the criteria, a difference of one point for one criterion does not equal a difference of one point for the other criteria. However, in the further analysis this is assumed to be the case, which make the results less reliable. The negative effects of this assumption will be reduced by incorporating multiple scenarios into the analysis (Schnaars, 1987) and judging the performance on the criteria as consistent as possible (see figure 20). Furthermore, in section 6.3 and 6.4 the results of using another performance valuation method based on frequency tables of the grading system and the results of using another method to choose an alternative based on multiple votes 'majority judgment' are compared to the results of this analysis in an attempt to validate the results.

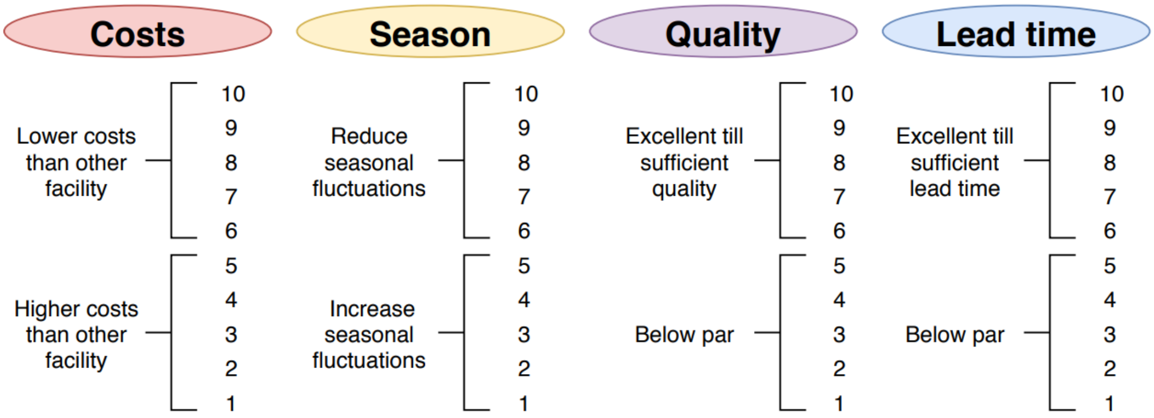


Figure 20: Performance valuation intervals used for the case study

5.3.8 Step 8: Define criteria weights

The stakeholders are asked to perform the BWM in order to define weights for de criteria. Before performing the BWM, the list of influencing variables and criteria (figure 17) with an explanation how the performance on the criteria are judged is shown to the stakeholders. However, the results of the analysis of the variables is not yet shown to prevent that the stakeholders base their answers on the values of the variables. The results of the BWM are shown in table 11.

Table 11: Results BWM

Stakeholders at Dewulf NL	**Costs**	**Season**	**Quality**	**Lead time**	**Consistency**
Removed from the public version					
Average Dewulf NL					

Stakeholders at Dewulf RO	**Costs**	**Season**	**Quality**	**Lead time**	
Removed from the public version					
Average Dewulf RO					

Stakeholders at Dewulf BE	**Costs**	**Season**	**Quality**	**Lead time**	
Removed from the public version					
Average Dewulf BE					

The consistency ratios of the stakeholders indicate that the consistency of the stakeholders is sufficient enough to continue with these criteria weights. The results show some differences between the stakeholder groups. Dewulf RO mainly focuses on the costs when making allocation decisions where Dewulf NL and BE also perceive quality and lead time as important criteria. Looking to the individual stakeholder, there is a big variety in which criterion is the most important. Each criterion is perceived to be the most important criterion by three stakeholders. This confirms that it is important to consider more criteria than only costs.

5.3.9 Step 9: Allocate production processes

Next, the performance scores are multiplied with the corresponding criteria weights. This is done separately for the three stakeholder groups. Accordingly, Opensolver is used to allocate the production processes in such a way that the sum of the weighted score is maximal while fulfilling the constraints. This step is repeated for each scenario developed in step 5. A screenshot of the allocation of stakeholder 1 for scenario 1 is shown in appendix B.3.

5.3.10 Step 10: Decision-making

In this step decisions about the allocation are made. These decisions are divided into long-term and short-term decisions. First, the information retained from the previous step is transformed into practical data. Accordingly, recommendations for long-term and short-term decisions are provided on which the allocation decisions can be made.

For long-term decision-making, an overview of the suggested allocation of all the production processes is made. This overview is made for each scenario and for each stakeholder group. Overall, the suggested allocation does not differ so much per scenario. The results for scenario 1 are presented below (figure 21 and 22). The allocations for the other scenarios is shown in appendix C.

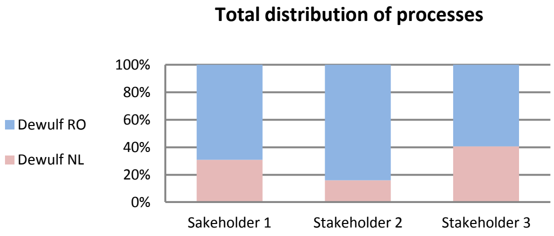


Figure 21: Total distribution of processes scenario 1

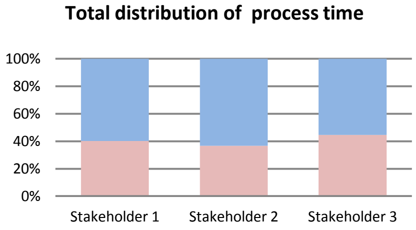
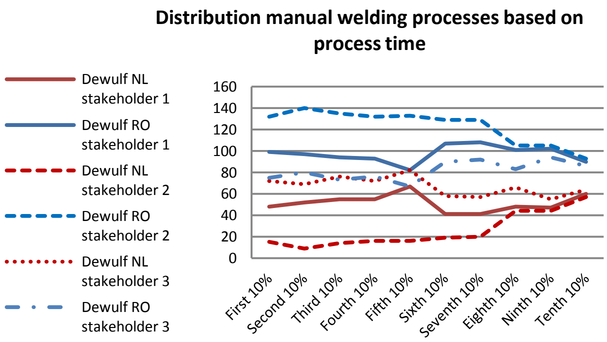


Figure 22: Total distribution of process time scenario 1

From the graphs it can be concluded that whatever stakeholder perspective is used, a lot of the production processes that are currently performed at Dewulf NL satisfy the stakeholders objectives better if they are being performed at Dewulf RO. In all scenarios it is actually more than 50 % of the processes. When looking only to stakeholder 2, it is even more than 80 % of the processes. Looking to the distribution of the process time, the analysis suggests to perform 60% of the total process time at Dewulf RO and 40% of the total process time at Dewulf NL.

To get an insight in which processes are allocated at Dewulf RO and which at Dewulf NL, graphs presenting the distribution based on the process time (figure 23 and 24), transportation dimensions (figure 25), and welding time per cubic meter of the assembly (figure 26 and 27) are drawn. The figures only show the results of scenario 1 (see appendix C for the other scenarios).



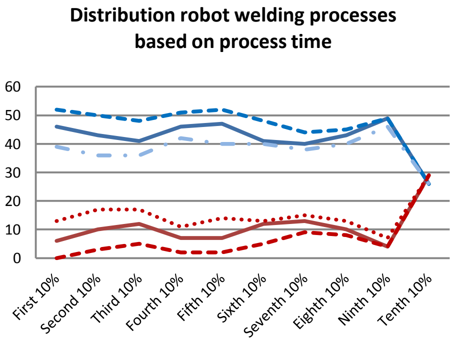


Figure 23: Distribution manual welding processes based on process time for scenario 1

Figure 24: Distribution robot welding processes based on process time for scenario 1

From the graphs based on the process time a clear trend cannot be made up. However, it can be concluded that for robot welding the longest 10% of the processes (49 minutes and longer) the distribution is about 50% to Dewulf RO and 50% to Dewulf NL, whereas for all processes shorter than 49 minutes this is about 80% to Dewulf RO and 20% to Dewulf NL. The reason for this is that when the robot processes are taking more than 49 minutes, the assemblies are usually too big for transportation or are very expensive to transport.

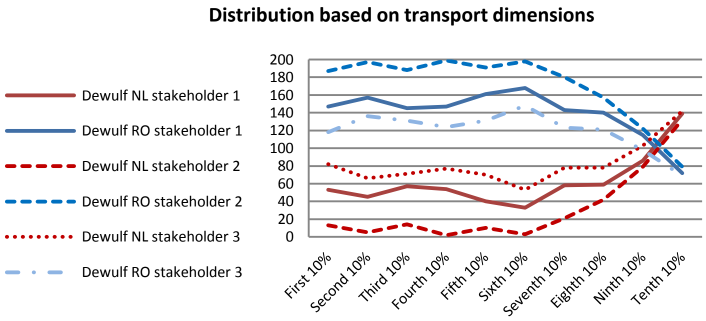
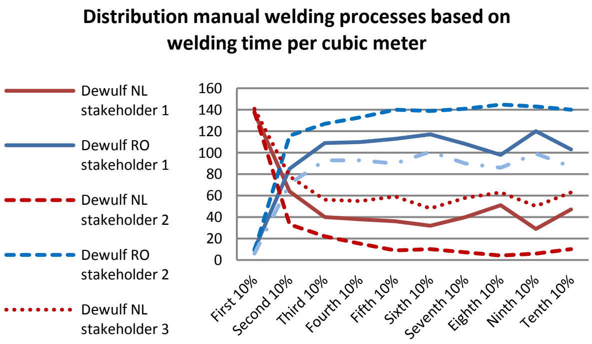


Figure 25: Distribution based on transport dimensions

From the graph based on the transport dimensions of the processes a certain trend can be made up. Production processes of small assemblies should more often be performed at Dewulf RO and production processes of big assemblies should more often be performed at Dewulf NL. This is because small assemblies have a lower transportation cost. The turning point lays around the 1,0m^3. However, just 10% of the assemblies are bigger than 1,0m^3.



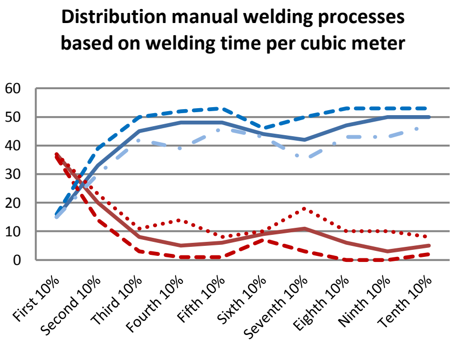


Figure 26: Distribution based on manual welding time per cubic meter for scenario 1

Figure 27: Distribution based on robot welding time per cubic meter scenario for 1

From the graphs based on the welding time per cubic meter of the assembly a similar trend can be made up. Big assemblies with a short welding time should be performed at Dewulf NL and small assemblies with a long welding time should be performed at Dewulf RO. The turning point lays around the 100 minutes per m^3. Here again, just 10% of the assemblies have less than 100 minutes per m^3.

Finally, a graph showing the total costs of the different allocations is shown in figure 28. A graphs of showing the total costs of all the scenarios is shown in appendix C.

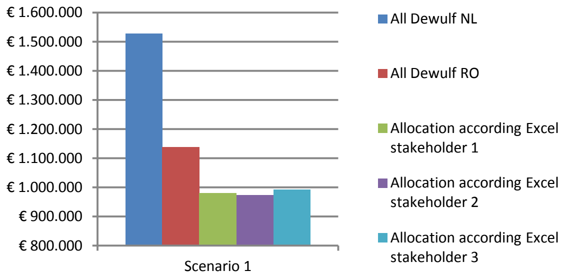


Figure 28: Total cost per allocation for scenario 1

The total costs are shown for the current situation (all Dewulf NL), a situation where all processes are performed at Dewulf RO (all Dewulf RO), and the suggested allocation according the stakeholders. It can be made up that the costs between the different stakeholder allocations does not differ that much. However, the difference between the current situation and the allocation according the stakeholders is quite big. About €500.000 cost savings per year could be achieved when the allocation suggestions of the analysis are followed.

For short-term decision-making a support tool is developed. Based on the results of the analysis, the tool shows at which facility a process should be performed to satisfy the objectives of the stakeholders the most. The tool asks a few questions about the processes and accordingly suggests a production location. A screenshot of the tool with an example process is show in appendix D.

5.4 Case study conclusions and recommendations

All the steps of the framework are successfully performed on the case study at Dewulf. The first step showed that with 2000 unique welding processes per year Dewulf NL performs a high variety of welding processes. The objectives and goals of eleven stakeholders, which are divided into three groups, are included in the decision support framework. Criteria that are used for the allocation choice are costs, seasonal fluctuations, quality, and lead time. On average, costs, quality and lead time appeared to be equally important and seasonal fluctuations just a little less. Influencing variables for the criteria are identified and investigated. Accordingly, four scenarios are sketched where certain variables are changed based on a dominant theme. The following four scenarios are developed:

1. The current situation
2. Labour costs in Romania increase faster than in the Netherlands in the next 5 years
3. Availability of skilled welders decreases in the Netherlands and the labour costs increase
4. Dewulf RO invests in a laser cutting machine of 6m, a press brake machine of 6,2m, and decreases the full costs of robot welding due to learning.

All the scenarios are analysed for each stakeholder group. From this analysis it can be concluded that it is a missed opportunity to not offshore any welding process to Dewulf RO. The criteria are maximal satisfied if about 60% of the production processes are allocated at Dewulf RO. This are mainly the small assemblies (less than 1,0m^3) and the assemblies with a big welding time per cubic meter (more than 100 minutes per m^3).

Even though the results show that many production processes should be allocated at Dewulf RO instead of Dewulf NL, moving all the assemblies to Dewulf RO (which may not be even possible due to maximum transport dimensions) is not recommended. When looking to scenario 2, the differences in total cost savings are probably too small to compensate for the investments costs and risks of moving all the processes (see appendix C). Following the suggested allocation can offer cost savings of €500.000 per year.

According the analysis, the stakeholders of Dewulf BE are a little bit more cautious with allocating production processes at Dewulf RO instead of Dewulf NL. This is due to the fact that they are more focused on lead time than the other stakeholders. It needs to be mentioned that the score on lead time for both facilities is judged based solely on a difference in transportation costs. If this would be done differently the results would be less different from the other stakeholders. Anyway, the point of conflict between the stakeholders is clear.

Based on the results of the analysis and discussions with the stakeholders about the results, the following is recommended to the Dewulf-group:

- Move the welding processes of small assemblies (assemblies smaller than 1m^3) that are produced more than 5 times per year to Dewulf RO. This applies to both robot and manual welding.
- Move the welding processes of bigger assemblies to Dewulf RO if there are more than 100 minutes of welding per square meter, provided that the assemblies fit in a truck.

6. Validation of the framework

The validation of the framework is done by discussing the results of the case study with the organization to validate the usefulness of the framework and performing three sensitivity checks. The sensitivity checks are done on just one scenario, namely scenario 1: current situation.

6.1 Feedback from the case study Dewulf

The results of the framework appeared to be of great use for the organization. Managers could immediately make long-term decisions after discussing the results. For some managers the results confirmed their gut feelings, for others the results where more surprising. Especially the results of the BWM, which showed that costs is certainly not the main criterion for the decision-making about the allocation of production processes.

Keeping the different stakeholder groups' perspectives separate appeared to provide a good insight in why some stakeholders would allocate the production processes differently than others. Knowing this, compromises could easily be made. However, the downside of keeping the different stakeholder perspectives separate is that it results in lots of graphs.

6.2 Sensitivity check: criteria weights

The first sensitivity check investigates what happens to the results of the analysis when the criteria weights are assigned differently. Two analysis to check the criteria weights sensitivity are performed. The first uses big adjusted criteria weights and the second uses small adjusted criteria weights. For the first the following three situations are compared (table 12).

Table 12: Big adjustments in criteria weights

	Costs	Season	Quality	Lead time
Stakeholder 1	0,26	0,21	0,31	0,22
Costs focussed	0,85	0,05	0,05	0,05
Not costs focused	0,10	0,30	0,30	0,30

The three situations are all analyzed with scenario 1 (the current situation). The total distribution and the distribution based on the welding time per square meter (min/m^3) are shown below.

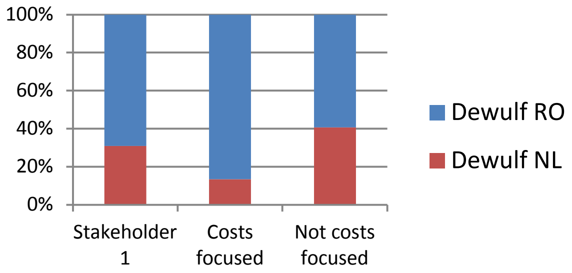


Figure 29: Distribution per criteria weights check (big adjustments)

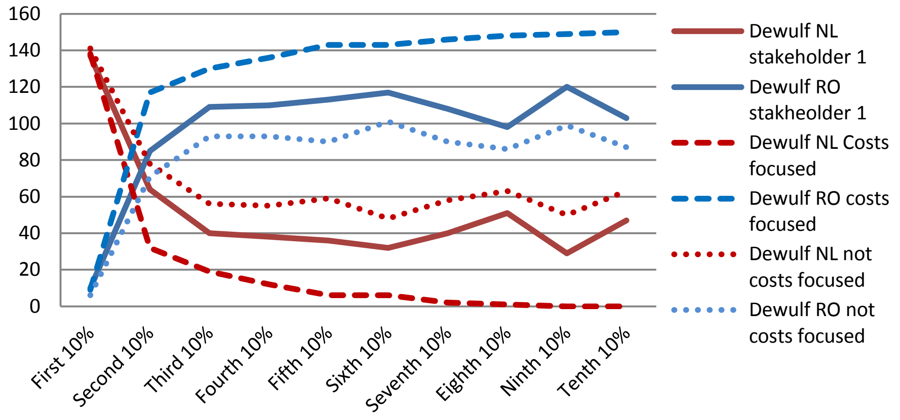


Figure 30: Distribution per based on welding time per cubic meter for the criteria weights check (big adjustments)

First of all, it can be concluded that changing the criteria weights adjust the results in the expected direction. When the criteria weights are more costs focused, more processes are allocated to Dewulf RO, which is the cheapest facility after the transportation costs are compensated by enough working hours. Secondly, it can be concluded that the results differ quit a lot. But the criteria weights are also changed quit a lot. To see whether the results are not too sensitive to a small change in the criteria weights, this analysis is repeated with smaller adjustments in criteria weights (table 13).

Table 13: Small adjustments in criteria weights

	Costs	Season	Quality	Lead time
Stakeholder 1	0,26	0,21	0,31	0,22
Costs focussed	0,32	0,18	0,25	0,25
Not costs focused	0,22	0,23	0,35	0,20

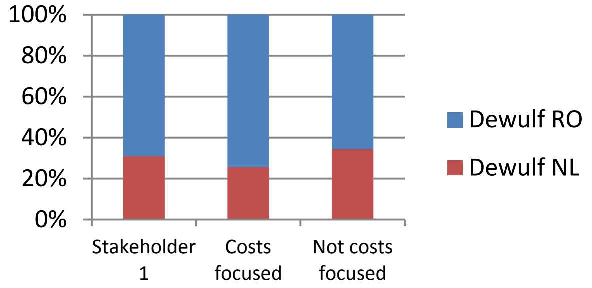


Figure 31: Distribution per criteria weights check (small adjustments)

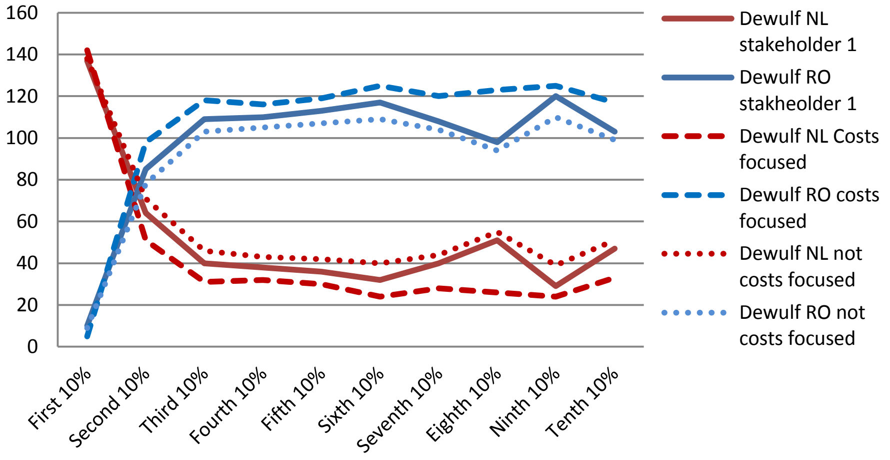


Figure 32: Distribution per based on welding time per cubic meter for the criteria weights check (small adjustments)

From these figures it can be made up that a small change in criteria weights does not lead to a big change in the results. This means that different criteria do influence the allocation, but not in a way that results become unreliable. Both these conclusions indicate that incorporating multiple objectives with different criteria in the allocation decision is possible. Whether the criteria weights really represent the objectives of the stakeholders is hard to validate. The only thing that can be concluded is that they move the allocation in the right direction and that the sensitivity of the criteria weights is acceptable.

6.3 Sensitivity check: criteria judgment

In the case study the criteria were judged with a score from 1 to 10. For the criterion ‘costs’ the first 10% most costs savings allocation alternatives were judged with a 10, the second 10% with a 9, and so on. However, when the expert judged the ‘quality’ criterion or when the author judged the ‘lead time’ criterion this grading system was not based on an exact 10% range per point. More likely, this was based on the Dutch grading system as known from school (both the expert and author are Dutch). This section attempts to compensate for this difference by adjusting the point range from the costs criterion to the same as the Dutch grading system. To do so, a frequency table of the grading system of a Dutch university (Radboud University) is used (see table 14).

Table 14: Frequency table Dutch grading system (Radboud University, 2017)

Score	How much assigned
10	0,8%
9	5,8%
8	26,6%
7	35,7%
6	31,0%

Al the grades from the table are sufficient. For insufficient grades (1 till 5) the same percentages are used in opposite order (so 5 = 31,0%, 4 = 35,7%, and so on). A comparison of the current judgment method and the method described above is shown in the figures below. For both methods the criteria weights of stakeholder 1 and the variables of scenario 1 are used.

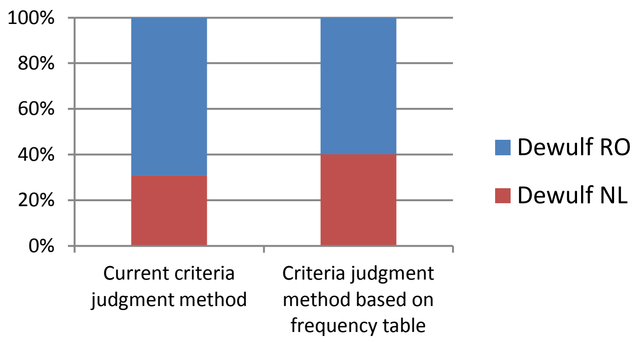


Figure 33: Total distribution per performance valuation method

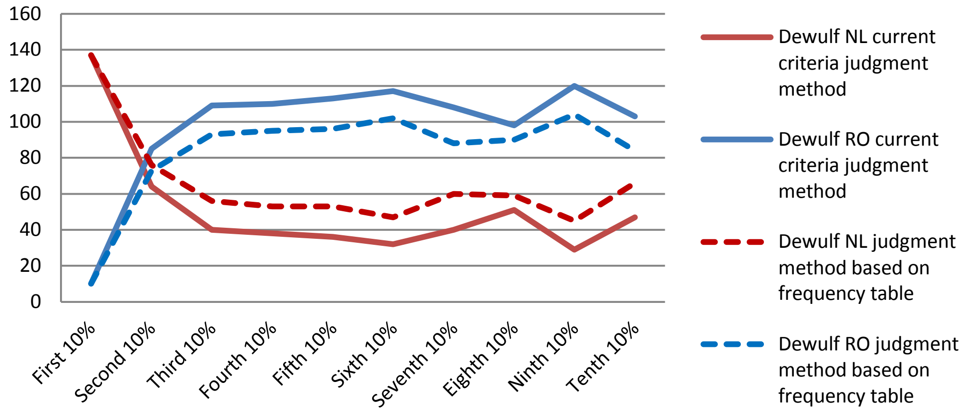


Figure 34: Distribution based on welding time per cubic meter for the performance valuation methods

It can be concluded that selecting another performance valuation method does affect the results. Since the judgment method based on the frequency tables of the Dutch grading system assigns less often a nine or ten and more often an eight, seven, or six, the differences between de facilities are less extreme (closer to a 50/50% distribution). Which of both judging methods better represents the objectives of the stakeholders is hard to say. However, just as with adjusting the criteria weights, the results do not change in a way they appear to be unreliable.

6.4 Sensitivity check: ranking the facilities

In the current framework the choice between the facilities is made by maximizing the sum of the criteria scores times the criteria weights (while fulfilling the constraints). Balinski and Laraki (2007) criticized this method for over- or underestimating alternatives because of some outliers. They proposed another method ‘majority judgment’ which bases the ranking on the median. The median is the middlemost score. The alternative with the highest median should be preferred above the other alternatives. Scores besides the median are perceived as being judged either too high or too low and are ignored. The number of criteria scores may be odd or even. If odd, there is one median. If even, the median is the lower of the two middlemost scores. When multiple alternatives share the highest median, the median is removed and a new median is found until there is a winner.

In this section the results of using the majority judgment method and maximizing the sum of the criteria scores are compared. For both methods the criteria weights of stakeholder 1 and the variables of scenario 1 are used.

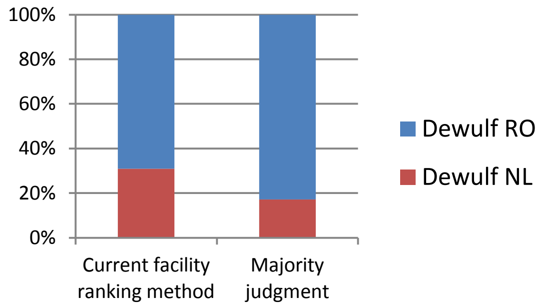


Figure 35: Total distribution per facility ranking method

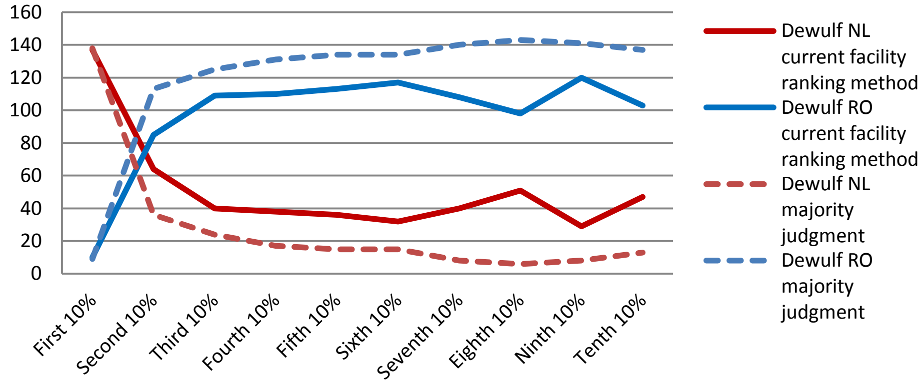


Figure 36: Distribution based on welding time per cubic meter for the facility ranking methods

From the figures it can be concluded that the method of ranking the facilities affect the results quite a lot. The results of majority judgment are in the case of the case study more extreme than just maximizing the total criteria score. In the case study of this thesis this does not seems to be an appropriate ranking method since the first two criteria are based on actual numbers and the two other criteria are averages of multiple variables which are not extremely high or low. This entails that if one of the first two criteria scores is very low this facility actually scores really low (i.e. extreme high costs or extreme bad for seasonal fluctuations), and this low score should not be ignored. However, when more quantitative criteria judged by managers, experts, or other persons are included in the analysis it is recommended to check whether the 'majority judgement method' provides different results.

7. Discussion

The framework presented in this thesis has been developed iteratively using inputs from theory and the case study. The framework is not a replacement of the decision-maker, it is a tool to support the decision-making progress. For the case study the framework provided useful information with which decision-makers can make substantiated decisions regarding the allocation of production processes. After developing the framework and executing the case study, the following claims can be made of why the results of this thesis are of practical use.

First of all, the unique combination of using MACMA, BWM, (spread sheet) simulation, and scenarios appears to be an excellent mix since the outputs and inputs of them have a big overlap. Moreover, the combination of methods provide better results than the independent methods on itself. For example, during the case study, the differences in objectives between the stakeholders were already visible after the BWM, but the consequences only became clear once the graphs were drawn. Due to this it can be said that (spread sheet) simulation is an excellent extension of the BWM since it provides a better insight in the meaning behind the criteria weights. Another combination, combining MACMA and (spread sheet) simulation, made it easy to keep the results of the different stakeholder (groups) separate. Where the results of different stakeholder (groups) in a MACMA are often merged, separately simulating the results of the different stakeholder (groups) make the differences and conflicts between them explicit. This appears to be of great value for the manager among the facilities.

The second claim is that the outcomes of the BWM for the case study confirm that, at least in some cases, decisions should not only be based on costs. Actually, only three of the eleven interviewed stakeholders mentioned costs as the most important criteria. Two stakeholders even indicated to perceive costs as the least important criterion. After further asking why they almost neglected the costs criterion, the stakeholders mentioned that other criteria like lead time or seasonal fluctuations can lead to much more irritation than spending more on a production process.

The third claim is that the differences and conflicts in objectives found by the framework appears to be an excellent starting point for the discussion between different facilities within an organization about improving the supply chain. It helps facilities to get an insight in the interests of other facilities and so create win-win situations.

The fourth claim is that drawing a scenario in the framework helps with long-term investment decisions at the facilities. Although the framework was initially intended to allocate production processes according facility variables, it is also possible to see what happens to the allocation if these facility variables change (for example due to a bigger laser or increased labour force).

All these claims described above contribute to the field of supply chain management and decision-making. Although these contributions have some practical applications, the framework does also have some limitations that are important to mention.

Firstly, the framework has not been extensively tested. It has been applied to just one case. Real validation of the framework is therefore not provided. Before speaking of a successful design, the framework should be tested on more real cases. Second, influencing variables can be quite different for other production processes like assembling or painting. This is also unknown because the framework is just tested for one type of production processes (welding). Third, for allocation problems with many production processes the decision supporting method will only be practical if the organization has all the needed information documented like the Dewulf-group (product dimensions, process times, etc.). Otherwise this is an extremely time-consuming job. Fourth, during evaluation of the BWM results of the case study it appeared that some stakeholders based their answers on how they perceive the performance on the criteria. For example, one stakeholder assigned a low importance to the quality criterion because he thought the quality is the same (or will be the same in the future) for both facilities and is therefore not important. However, whether the quality is the same for both facilities should be analysed and not judged by one stakeholder. If the quality appears to be the same for both facilities this criterion will automatically become not important. Fifth, just as with all other simulations, the outcomes are as correct as the input. Since many assumptions have to be made for the input of the framework, the reliability of the output cannot be guaranteed. One of these assumptions is assigning a score to the performance on the criteria. Judging of the different performances and normalizing it to the same scale is quite challenging. For qualitative criteria this assumption seems quite obvious, but even for quantitative criteria the results differ depending on which performance valuation method is chosen. The sensitivity checks showed that for the case study in this thesis the robustness of the chosen methods is quite good. It is however uncertain whether this will also be the case for other cases. Due to the last limitation it can be concluded that the framework does not help to find an optimal solution but rather pushes the decision in the right direction.

8. Conclusion and recommendations

In this dissertation, a new decision support framework to allocate production processes within multi-facility manufacturing organizations has been developed and applied to the allocation problem of the Dewulf-group. As the name of the support framework implies, the framework is optimized to ensure an optimal allocation of production processes. Based on the experiences of the case study and applicable literature the following conclusions can be drawn.

From the user feedback and the three sensitivity checks that are performed it can be concluded that, at least for the case study, the ten-step framework does provide support to managers making decisions regarding the allocation of production processes. All the initial stated requirements are fulfilled by the framework. Moreover, from the three sensitivity checks it can be concluded that the framework provides reliable results. Another conclusion that can be drawn is that the allocation should not be based on only cost related decision variables, as existing literature already emphasized. The final conclusion is that including quantitative and qualitative criteria in a decision-making process is a challenging exercise. Especially the step to valuate the performances on quantitative criteria, and normalize these scores so that they can be compared to scores assigned to quantitative performances. This might be the reason that a decision support method for the allocation of production processes that considers both qualitative an qualitative criteria was not yet in existence. Although the proposed valuation method in this framework is not yet optimal, it is a acceptable method that proved its reliability in the case study.

Based on the conclusion above, the a handful of recommendations for further research can be stated. Most recommendations are about the validation of the framework since the study performed by the author is constructed from the input of just one case study and applicable literature. The current framework is only applied on welding processes of an agricultural machinery manufacturing organization. By applying the newly developed framework on a wide variety of production processes, the framework could even provide support on other processes (e.g. assembling, painting) or in other sectors (e.g. medical equipment manufactures or software development), and prove its generic effectiveness. In addition to the recommendation above, this can be extended by including more than two production facilities to the framework. This allows the measurement of effectiveness for particular cases. Hence, the framework might possibly also prove its effectiveness in big multinational manufacturing organizations.

Other recommendations are more focussed on the further development of the framework. The most challenging step of the framework, the judgement of the performance on the criteria, is open for improvement. Existing literature is not sufficient enough to select a common language that can be used to normalize quantitative and qualitative performances. This common language should be developed whereby frequency tables can play an important role. Maybe different frequency tables are required for different criteria. Furthermore, it should be investigated whether majority judgment is a better method to rank the facilities when more qualitative criteria are involved in the analysis.

When the above mentioned parts are investigated, the next step is to further develop the detailed design of the framework. A web-based version or computer program of the decision support framework should be developed to increase the ease of communication of the framework to interested organizations.

Reflection

First of all, I like to mention that I really liked it to perform my thesis project in an organization environment. This is mainly because of the fact that I am a more practical type and a more interested in 'production processes' than reading many journals or doing in depth literature reviews. Moreover, I am highly interested in the machinery manufacturing industry in which the case company is operating. This, together with my trip to the production facility in Romania to investigate the facility-related variables, made this a dream thesis for me. Although it was sometimes hard to find a good balance between theory and practice I highly recommend other students to also perform their thesis at an organization in which they are interested and learn as much as possible in your last few student months.

I also liked the iterative nature of the designing process. Personally, I think this is the only right way of designing something. Especially when you are not yet an expert, it is impossible to define all the requirements, objectives or design steps upfront. During my thesis project I learned a lot about:

- How decisions are made within multi-facility organizations.
- How objectives can highly differ between stakeholders within an organization.
- How important it is to consider more variables than only costs.
- Romania and how production facilities in Eastern Europe look like.
- How to use Excel for spread sheet simulations and how to use linear solvers to find optimal solutions.

The following courses from the Management of Technology curriculum have a connection with this thesis:

- **Financial Management** for reading a balance sheet and calculating labour costs based on an annual growth.
- **Social and Scientific Values** for the importance of involving multiple stakeholders in decision-making.
- **Inter- and Intra-organisation Decision-Making** for getting insight on how big decisions are made within organizations.
- **Technology Battles (elective)** for introducing the Best-Worst Method and retracting influencing variables from multiple papers.
- **Logistics and Supply Chain Innovations (elective)** for introducing the SCOR model and teaching the basics of supply chains in organizations.
- **Preparation for Master Thesis** for defining requirements and creating a thesis structure with a sound design approach.

The most difficult part of the designing process was the establishment of the requirements. Especially defining the requirements in a SMART way and finding good sources for these requirements. I think I did not succeed to establish a comprehensive list of SMART requirements because for me the requirements of the case company where quit clear, but for a more generic decision support framework these were not sufficient. If I would redo the whole project I would spend more time on defining SMART requirement by interviewing organizations who might be interested in the framework.

References

Alvarez, E. (2007). Multi-plant production scheduling in SMEs. *Robotics and Computer-Integrated Manufacturing, 23*(1), 608-613.

Amer, M., Daim, T. U., & Jetter, A. (2013). A review of scenario planning. *Futures, 46*, 23-40.

Balinski, M., & Laraki, R. (2007). A theory of measuring, electing, and ranking. *Proceedings of the National Academy of Sciences, 104*(21), 8720-8725.

Bhatnagar, R., & Sohal, A. (2005). Supply chain competitiveness: meaning the impact of location factors, uncertainty and manufacturing practices. *Technovation, 25*(5), 443-456.

Bryson, J. (2004). What to do when stakeholders matter: stakeholder identification and analysis techniques. *Public management review, 6*(1), 21-53.

Dachs, B., Ebersberger, B., Kinkel, S., & Waser, B. (2006). Offshoring of production-a European perspective. *Bulletin Number*.

Dale, B., & Cunningham, M. (1984). The importance of Factors Other Than Cost Considerations in Make or Buy Decisions. *International Journal of Operations & Production Management, 4*(3), 43-54.

Delis, A., Driffield, N., & Temouri, Y. (2017). The global recession and the shift to re-shoring: Myth or reality? *Journal of Business Research*.

Dewulf. (2014). *Geschiedenis*. Retrieved from Dewulf: http://www.dewulfgroup.com/nl/geschiedenis-34.htm

Draffin, A. (2010). *Methodology vs framework - why waterfall and agile are not methodologies*. Retrieved from IT Strategies: https://morgoth.wordpress.com/2010/04/07/methodology-vs-framework-why-waterfall-and-agile-are-not-methodologies/

Dym, C., Little, P., Orwin, E., & Spjut, E. (2009). *Engineering Design: A Project-Based Introduction* (3rd Edition ed.). New York: John Wiley & Sons.

Fahimnia, B., Farahani, R. Z., Marian, R., & Luong, L. (2013). A review and critique on integrated production-distribution planning models and techniques. *Journal of Manufacturing Systems, 32*(1), 1-19.

Fleischmann, B., Ferber, S., & Henrich, P. (2006). Strategic planning of BMW's global production network. *Interfaces, 36*(3), 194-208.

Garvin, D. A. (1998). The Processes of Organization and Management. *Sloan management review, 39*(4), 33.

Hax, A., & Meal, H. (1973). Hierarchical integration of production planning and scheduling.

Ishizaka, A., & Nemery, P. (2013). *Multi-criteria decision analysis: methods and software.* John Wiley & Sons.

Jones, T., Atkinson, H., Lorenz, A., & Harris, P. (2012). *Strategic Managerial Accounting: Hospitality, Tourism & Events Applications.* Oxford: Goodfellows.

Klinkel, S., & Maloca, S. (2009). Drivers and antecedents of manufacturing offshoring and backshoring - A German perspective. *Journal of Purchasing and Supply Management, 15*(3), 154-165.

Liepina, L., & Kirikova, M. (2011). SCOR Based ISS Requirements Identification. *International Conference on Business Information Systems*, 232-243.

Lunenburg, F. C. (2011). Decision Making in Organizations. *International Journal of Management, Business, and Administration, 15*(1).

MacCarthy, B., & Atthirawong, W. (2003). Factors affecting location decisions in international operations - a Delphi study. *International Journal of Operations & Produciton Management, 23*(7), 794-818.

Macharis, C., De Witte, A., & Ampe, J. (2009). The multi-actor, multi-criteria analysis methodology (MAMCA) for the evaluation of transport projects: Theory and practice. *Journal of Advanced transportation, 43*(2), 183-202.

Mentzer, J., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (2001). Defining Supply Chain Management. *Journal of Business Logistics, 22*(2), 1-25.

Mihaylov, I. (2018). *Labour costs growth in Romania, Bulgaria highest in EU in Q4 2017 - Eurostat*. Retrieved from SeeNeews: https://seenews.com/news/labour-costs-growth-in-romania-bulgaria-highest-in-eu-in-q4-2017-eurostat-605390

Olhager, J. (2012). The role of decoupling points in value chain management. *Modelling value*, 37-47.

Prasad, S., & Sounderpandian, J. (2003). Factors influencing global cupply chain efficiency: implicaitons for information systems. *Supply Chain Management: An international Journal, 8*(3), 241-250.

Radboud University. (2017). *Dutch grading system*. Retrieved from Radboud University: https://www.ru.nl/currentstudents/graduation-beyond/graduation-exams-0/dutch-grading-system/

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., . . . Stringer, L. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management, 90*, 1933-1949.

Rezaei, J. (2015). Best-worst multi-criteria decision-making method. *Omega, 53*, 49-57.

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega, 64*, 126-130.

Roth, A. V., & Miller, J. G. (1992). Success factors in manufacturing. *Business Horizons, 35*(4), 73-81.

Schnaars, S. (1987). How to develop and use scenarios. *Long range planning, 20*(1), 105-114.

Sein, M. K., Purao, S., Henfridsson, O., & Rossi, M. (2011). Action Design Research. *MIS Quarterly, 35*(1), 37-56.

Simchi-Levi, D., & Kaminski, P. (2000). *Designing and managing the supply chain - concepts, strategies and case studies.* McGraw- Hill.

Snoo, A. d. (2016). *Produceren in Nederland of in lagelonenlanden? Reshoring en innovatie: informatie, praktijkvoorbeelden, routwijzer.* Retrieved from KVK: https://www.kvk.nl/advies-en-informatie/innovatie/reshoring/

Supply Chain Council, Incl. (2010). *Supply Chain Operations Reference (SCOR) model.*

Swamidass, P. M., & Newell, W. t. (1987). Manufacturing strategy, environmental uncertainty and performance: A path analytifcal model. *Management Science, 33*(4), 509-524.

Terzi, S., & Cavalieri, S. (2004). Simulation in the supply chain context: a survey. *Computers in industry, 53*(1), 3-16.

UWV. (2017). *Kansrijke beroepen: Waar is de arbeidsmarkt krap? Landelijk overzicht.* Amsterdam.

Verschuren, P., & Hartog, R. (2005). Evaluation in Design-Oriented Research. *Quality & Quantity, 39*, 733-762.

Vidal, C. J., & Goetschalckx, M. (1997). Strategic production-distribution models: A critical review with emphasis on global supply chain models. *European Journal of Operational Research, 98*(1), 1-18.

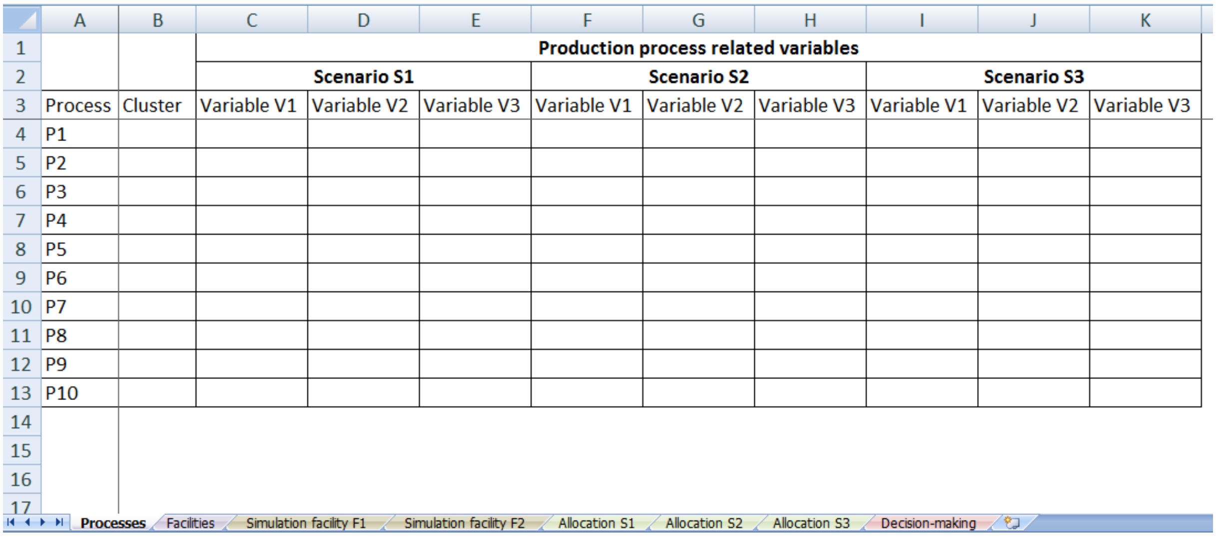
Visser, E. (2000). The outsourcing dilemma: a composite approach to the make or buy decision. *Management Decision, 38*(1), 43-50.

Vujičić, M., Papić, M., & Blagojević, M. (2017). Comparative Analysis of Objective Techniques for Criteria Weighing in Two MCDM Methods on Example of an Air Conditioner Selection. *Tehnika, 72*(3), 422-429.

Zenjiro, I. (2012). *Understand Supply Chain Management through 100 words.* KOUGYOUCHOUSAKAI.

Appendix A – Decision support framework template

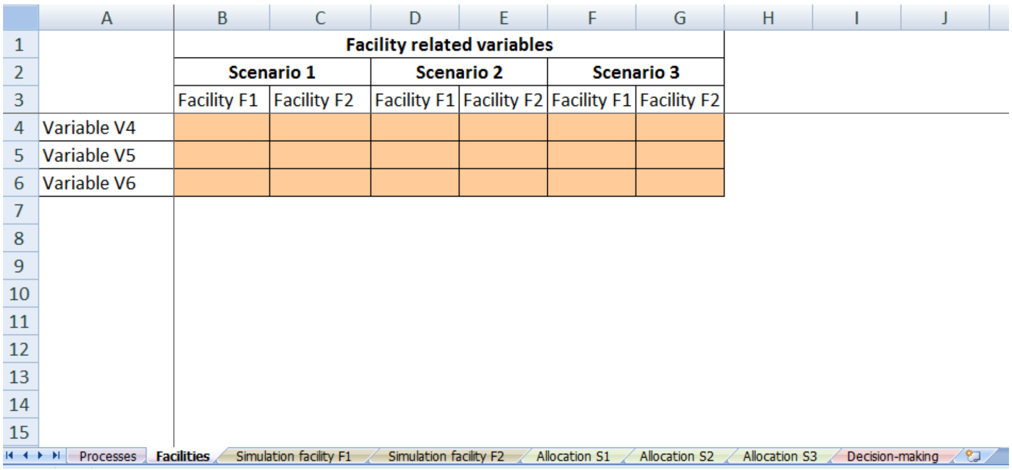
The simulation in Microsoft Excel is performed on multiple worksheets. The first step is to list the production processes in column A of the first worksheet (see figure A.1).



		Production process related variables								
		Scenario S1			Scenario S2			Scenario S3		
Process	Cluster	Variable V1	Variable V2	Variable V3	Variable V1	Variable V2	Variable V3	Variable V1	Variable V2	Variable V3
P1										
P2										
P3										
P4										
P5										
P6										
P7										
P8										
P9										
P10										

Figure A.1: Worksheet production processes

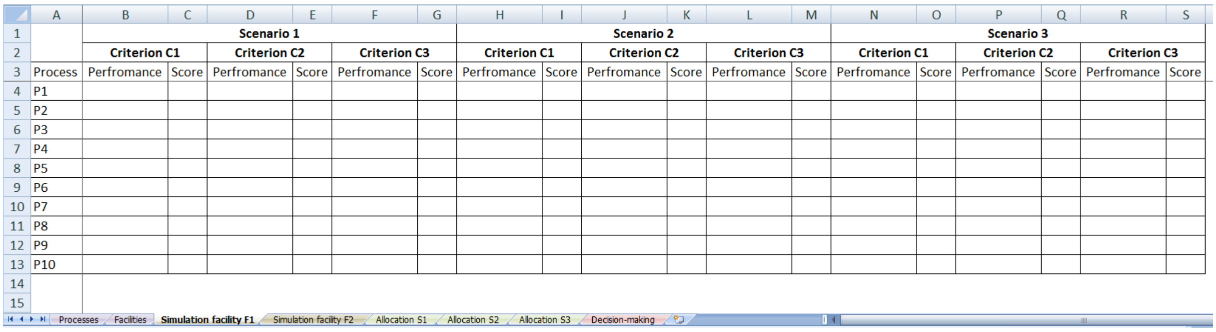
The second step is to list de selected facilities in the first row of the second worksheet (see figure A.2).



	Facility related variables					
	Scenario 1		Scenario 2		Scenario 3	
	Facility F1	Facility F2	Facility F1	Facility F2	Facility F1	Facility F2
Variable V4						
Variable V5						
Variable V6						

Figure A.2: Worksheet facilities

The third step is to identify the criteria for the decision-making. The criteria are listed in the second row of the third and fourth worksheet (see figure A.3).



	Scenario 1						Scenario 2						Scenario 3					
	Criterion C1		Criterion C2		Criterion C3		Criterion C1		Criterion C2		Criterion C3		Criterion C1		Criterion C2		Criterion C3	
Process	Perfromance	Score	Perfromance	Score	Perfromance	Score	Perfromance	Score	Perfromance	Score	Perfromance	Score	Perfromance	Score	Perfromance	Score	Perfromance	Score
P1																		
P2																		
P3																		
P4																		
P5																		
P6																		
P7																		
P8																		
P9																		
P10																		

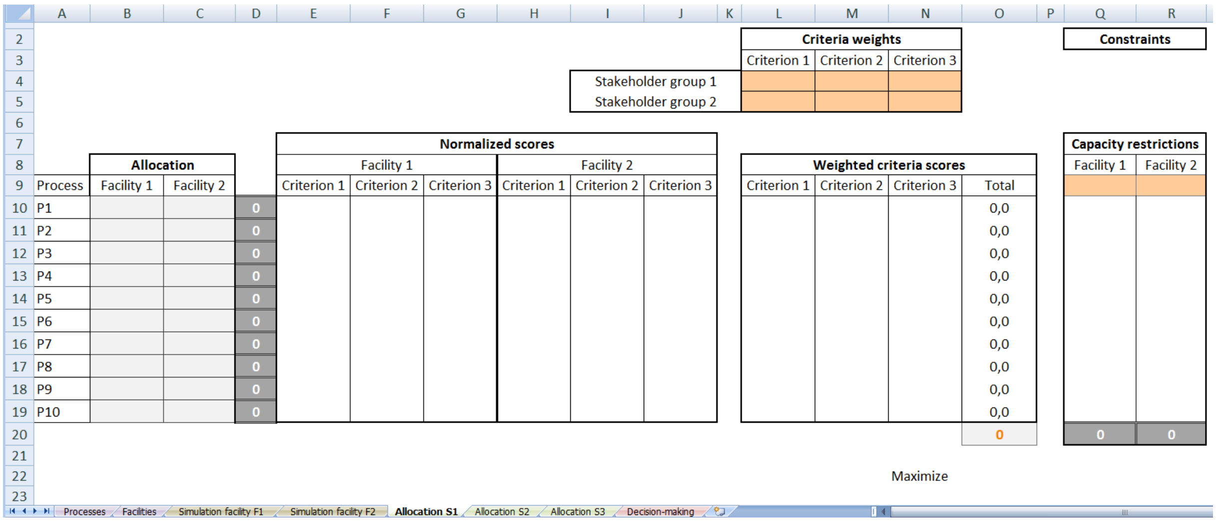
Figure A.3: Worksheet simulate processes at the facilities

The fourth step is to identify and analyze the variables that analyze the performance of the criteria. Production-process-related variables are listed in the first worksheet under scenario 1 (see figure A.1). Facility-related variables are listed in the second worksheet under scenario 1 (see figure A.2).

In the fifth step scenarios are developed. The adjusted variables are listed in the first two worksheets. Columns have to be added if more than three scenarios are developed.

The sixth step is to simulate the performances on the criteria. The performances are listed in simulation worksheets. In the seventh step these performances are assigned with a score. This score is put in the column next to the performances.

In step eight the criteria weights are defined. The criteria weights are put in the under criteria weights in the allocation sheets (see figure A.4).



	Criteria weights		
	Criterion 1	Criterion 2	Criterion 3
Stakeholder group 1			
Stakeholder group 2			

Constraints

	Allocation			Normalized scores						Weighted criteria scores				Capacity restrictions	
				Facility 1			Facility 2							Facility 1	Facility 2
Process	Facility 1	Facility 2		Criterion 1	Criterion 2	Criterion 3	Criterion 1	Criterion 2	Criterion 3	Criterion 1	Criterion 2	Criterion 3	Total		
P1			0										0,0		
P2			0										0,0		
P3			0										0,0		
P4			0										0,0		
P5			0										0,0		
P6			0										0,0		
P7			0										0,0		
P8			0										0,0		
P9			0										0,0		
P10			0										0,0		
													0	0	0

Maximize

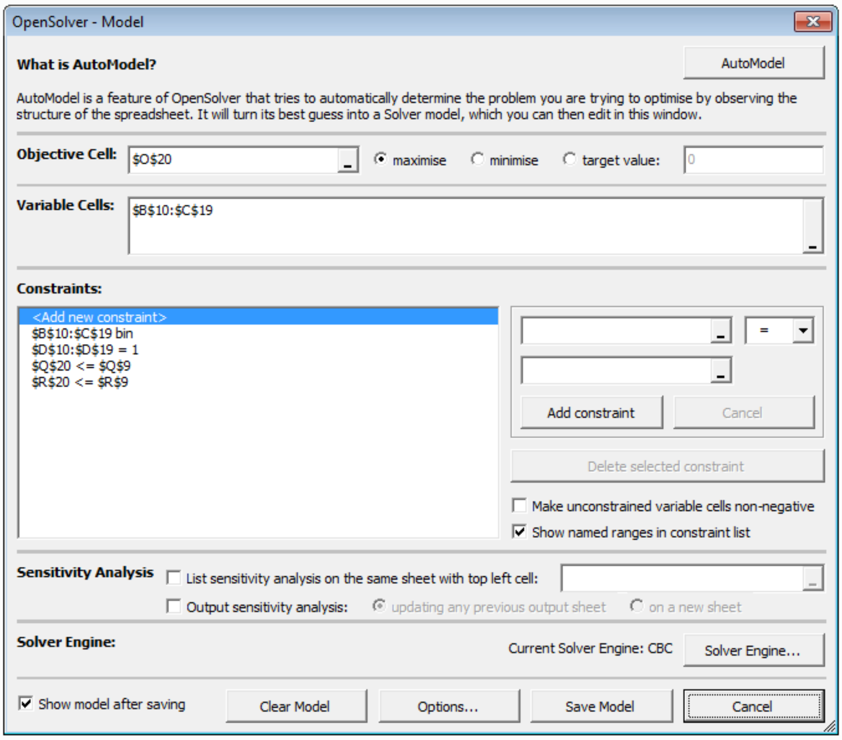
Figure A.4: Worksheet allocation

The criteria scores of both facilities should be normalized and put into columns E till J. For each process, either column B or C is 1. When column B is 1 the process is performed at facility 1 and when Column C is 1 the process is performed at facility 2. To show how to program the weighted criteria scores, an example of cell L10 is provided:

$$\$L\$4 * (E10*B10 + H10*C10)$$

Opensolver is used to select at which facility the process should be performed by putting a 1 or 0 in the cells in column B and C while maximizing the total weighted criteria score in cell O20 (see figure

A.4). Opensolver can be downloaded from: https://opensolver.org/. Opensolver selects the facility where the weighted total criteria score is the highest for each production process. Moreover, it is possible to program multiple constraints. Opensolver should be programmed as in figure A.5.



What is AutoModel?

AutoModel is a feature of OpenSolver that tries to automatically determine the problem you are trying to optimise by observing the structure of the spreadsheet. It will turn its best guess into a Solver model, which you can then edit in this window.

Objective Cell: $O$20 ● maximise ○ minimise ○ target value: 0

Variable Cells: $B$10:$C$19

Constraints:

<Add new constraint>
$B$10:$C$19 bin
$D$10:$D$19 = 1
$Q$20 <= $Q$9
$R$20 <= $R$9

☐ Make unconstrained variable cells non-negative
☑ Show named ranges in constraint list

Sensitivity Analysis ☐ List sensitivity analysis on the same sheet with top left cell:
☐ Output sensitivity analysis: ● updating any previous output sheet ○ on a new sheet

Solver Engine: Current Solver Engine: CBC

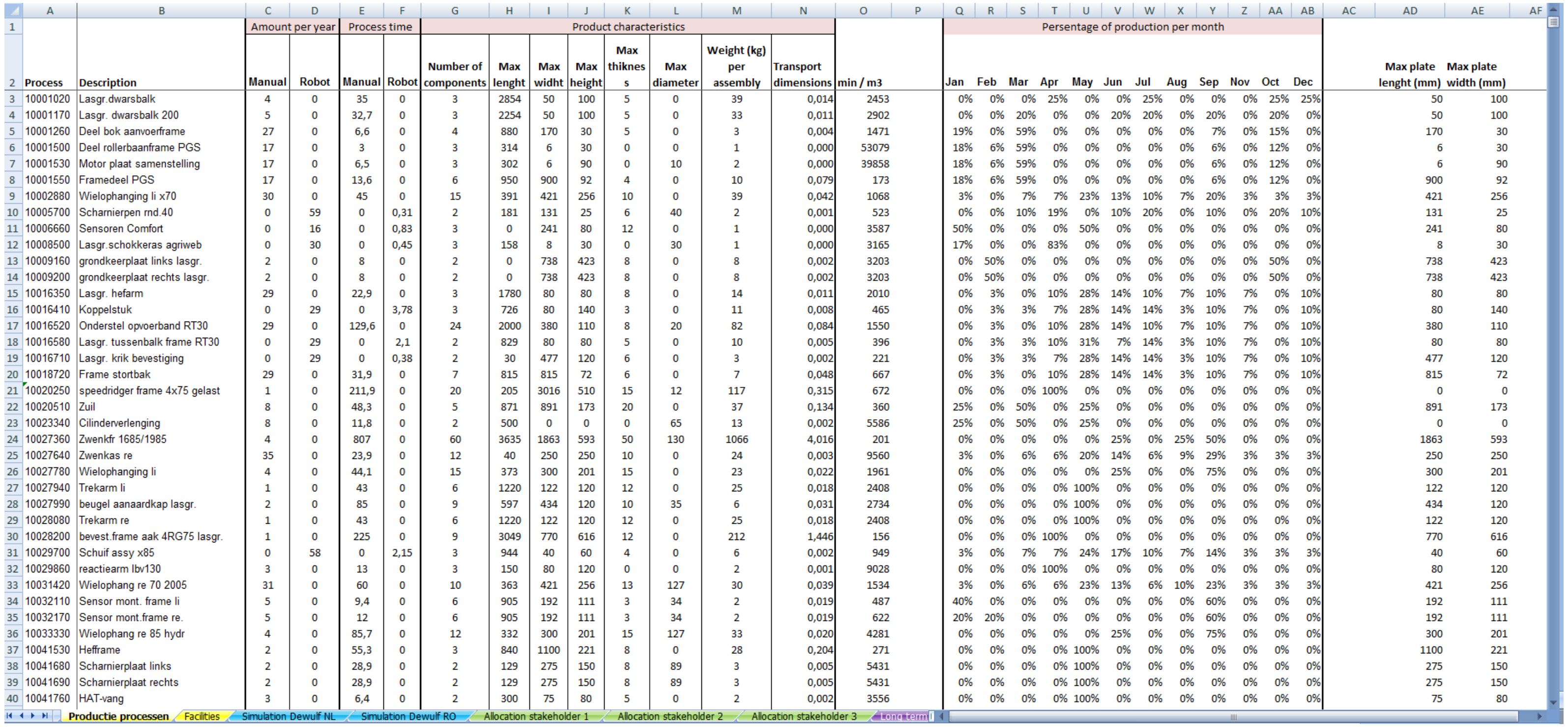
☑ Show model after saving

Figure A.5: Opensolver

Appendix B – Case study spreadsheet

Due to confidentiality reasons this document cannot be fully disclosed. A screenshot of every sheet is shown below.

B.1 Production processes sheet

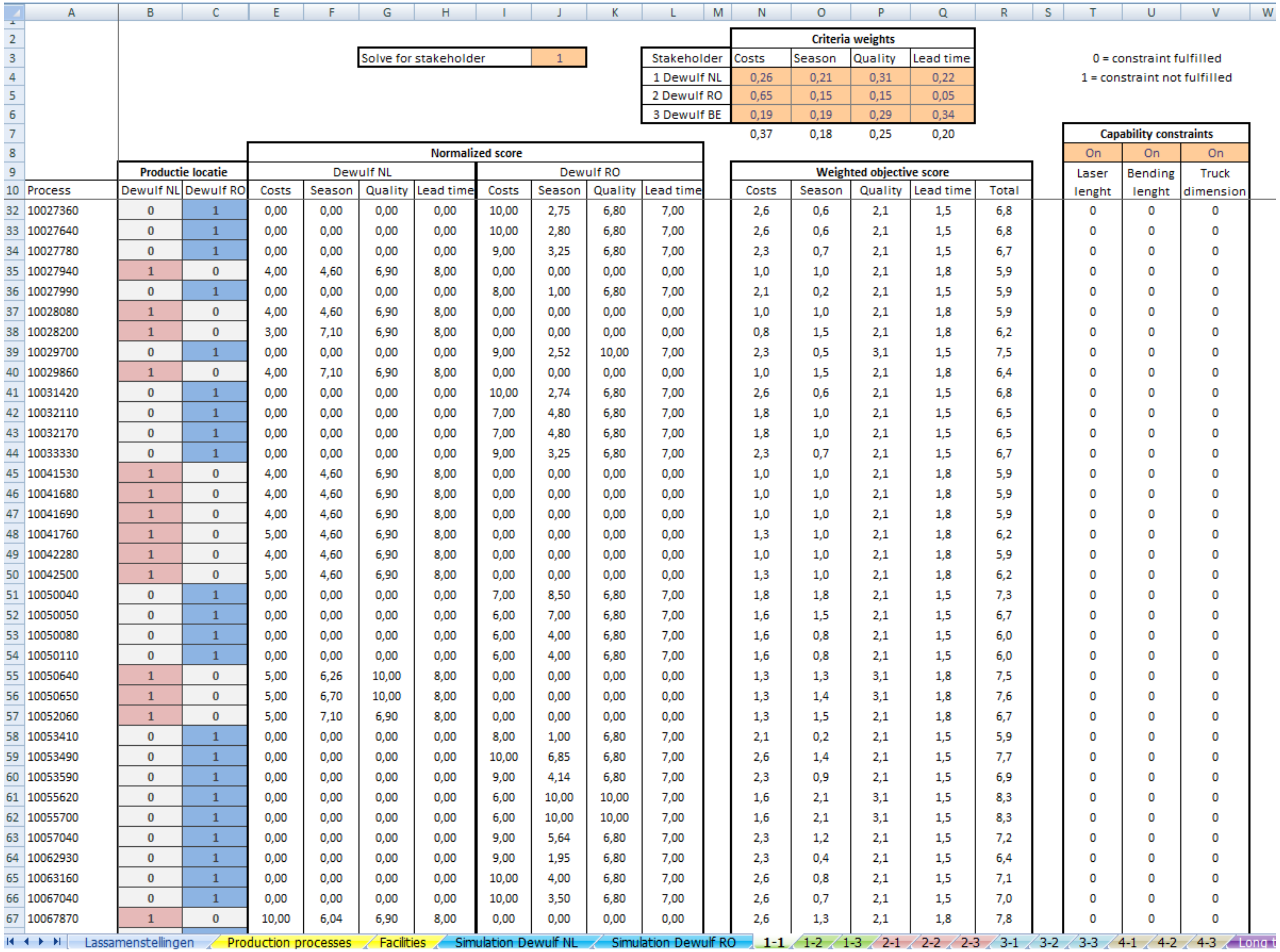


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF
1			Amount per year		Process time		Product characteristics										Persentage of production per month															
2	Process	Description	Manual	Robot	Manual	Robot	Number of components	Max lenght	Max widht	Max height	Max thiknes s	Max diameter	Weight (kg) per assembly	Transport dimensions	min / m3		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Nov	Oct	Dec		Max plate lenght (mm)	Max plate width (mm)	
3	10001020	Lasgr.dwarsbalk	4	0	35	0	3	2854	50	100	5	0	39	0,014	2453		0%	0%	0%	25%	0%	0%	25%	0%	0%	0%	25%	25%		50	100	
4	10001170	Lasgr. dwarsbalk 200	5	0	32,7	0	3	2254	50	100	5	0	33	0,011	2902		0%	0%	20%	0%	0%	20%	20%	0%	20%	0%	20%	0%		50	100	
5	10001260	Deel bok aanvoerframe	27	0	6,6	0	4	880	170	30	5	0	3	0,004	1471		19%	0%	59%	0%	0%	0%	0%	0%	7%	0%	15%	0%		170	30	
6	10001500	Deel rollerbaanframe PGS	17	0	3	0	3	314	6	30	0	0	1	0,000	53079		18%	6%	59%	0%	0%	0%	0%	0%	6%	0%	12%	0%		6	30	
7	10001530	Motor plaat samenstelling	17	0	6,5	0	3	302	6	90	0	10	2	0,000	39858		18%	6%	59%	0%	0%	0%	0%	0%	6%	0%	12%	0%		6	90	
8	10001550	Framedeel PGS	17	0	13,6	0	6	950	900	92	4	0	10	0,079	173		18%	6%	59%	0%	0%	0%	0%	0%	6%	0%	12%	0%		900	92	
9	10002880	Wielophanging li x70	30	0	45	0	15	391	421	256	10	0	39	0,042	1068		3%	0%	7%	7%	23%	13%	10%	7%	20%	3%	3%	3%		421	256	
10	10005700	Scharnierpen rnd.40	0	59	0	0,31	2	181	131	25	6	40	2	0,001	523		0%	0%	10%	19%	0%	10%	20%	0%	10%	0%	20%	10%		131	25	
11	10006660	Sensoren Comfort	0	16	0	0,83	3	0	241	80	12	0	1	0,000	3587		50%	0%	0%	0%	50%	0%	0%	0%	0%	0%	0%	0%		241	80	
12	10008500	Lasgr.schokkeras agriweb	0	30	0	0,45	3	158	8	30	0	30	1	0,000	3165		17%	0%	0%	83%	0%	0%	0%	0%	0%	0%	0%	0%		8	30	
13	10009160	grondkeerplaat links lasgr.	2	0	8	0	2	0	738	423	8	0	8	0,002	3203		0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	50%	0%		738	423	
14	10009200	grondkeerplaat rechts lasgr.	2	0	8	0	2	0	738	423	8	0	8	0,002	3203		0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	50%	0%		738	423	
15	10016350	Lasgr. hefarm	29	0	22,9	0	3	1780	80	80	8	0	14	0,011	2010		0%	3%	0%	10%	28%	14%	10%	7%	10%	7%	0%	10%		80	80	
16	10016410	Koppelstuk	0	29	0	3,78	3	726	80	140	3	0	11	0,008	465		0%	3%	3%	7%	28%	14%	14%	3%	10%	7%	0%	10%		80	140	
17	10016520	Onderstel opvoerband RT30	29	0	129,6	0	24	2000	380	110	8	20	82	0,084	1550		0%	3%	0%	10%	28%	14%	10%	7%	10%	7%	0%	10%		380	110	
18	10016580	Lasgr. tussenbalk frame RT30	0	29	0	2,1	2	829	80	80	5	0	10	0,005	396		0%	3%	3%	10%	31%	7%	14%	3%	10%	7%	0%	10%		80	80	
19	10016710	Lasgr. krik bevestiging	0	29	0	0,38	2	30	477	120	6	0	3	0,002	221		0%	3%	3%	7%	28%	14%	14%	3%	10%	7%	0%	10%		477	120	
20	10018720	Frame stortbak	29	0	31,9	0	7	815	815	72	6	0	7	0,048	667		0%	3%	0%	10%	28%	14%	14%	3%	10%	7%	0%	10%		815	72	
21	10020250	speedridger frame 4x75 gelast	1	0	211,9	0	20	205	3016	510	15	12	117	0,315	672		0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%		0	0	
22	10020510	Zuil	8	0	48,3	0	5	871	891	173	20	0	37	0,134	360		25%	0%	50%	0%	25%	0%	0%	0%	0%	0%	0%	0%		891	173	
23	10023340	Cilinderverlenging	8	0	11,8	0	2	500	0	0	0	65	13	0,002	5586		25%	0%	50%	0%	25%	0%	0%	0%	0%	0%	0%	0%		0	0	
24	10027360	Zwenkfr 1685/1985	4	0	807	0	60	3635	1863	593	50	130	1066	4,016	201		0%	0%	0%	0%	0%	25%	0%	25%	50%	0%	0%	0%		1863	593	
25	10027640	Zwenkas re	35	0	23,9	0	12	40	250	250	10	0	24	0,003	9560		3%	0%	6%	6%	20%	14%	6%	9%	29%	3%	3%	3%		250	250	
26	10027780	Wielophanging li	4	0	44,1	0	15	373	300	201	15	0	23	0,022	1961		0%	0%	0%	0%	0%	25%	0%	0%	75%	0%	0%	0%		300	201	
27	10027940	Trekarm li	1	0	43	0	6	1220	122	120	12	0	25	0,018	2408		0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%		122	120	
28	10027990	beugel aanaardkap lasgr.	2	0	85	0	9	597	434	120	10	35	6	0,031	2734		0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%		434	120	
29	10028080	Trekarm re	1	0	43	0	6	1220	122	120	12	0	25	0,018	2408		0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%		122	120	
30	10028200	bevest.frame aak 4RG75 lasgr.	1	0	225	0	9	3049	770	616	12	0	212	1,446	156		0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%		770	616	
31	10029700	Schuif assy x85	0	58	0	2,15	3	944	40	60	4	0	6	0,002	949		3%	0%	7%	7%	24%	17%	10%	7%	14%	3%	3%	3%		40	60	
32	10029860	reactiearm lbv130	3	0	13	0	3	150	80	120	0	0	2	0,001	9028		0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%		80	120	
33	10031420	Wielophang re 70 2005	31	0	60	0	10	363	421	256	13	127	30	0,039	1534		3%	0%	6%	6%	23%	13%	6%	10%	23%	3%	3%	3%		421	256	
34	10032110	Sensor mont. frame li	5	0	9,4	0	6	905	192	111	3	34	2	0,019	487		40%	0%	0%	0%	0%	0%	0%	0%	60%	0%	0%	0%		192	111	
35	10032170	Sensor mont.frame re.	5	0	12	0	6	905	192	111	3	34	2	0,019	622		20%	20%	0%	0%	0%	0%	0%	0%	60%	0%	0%	0%		192	111	
36	10033330	Wielophang re 85 hydr	4	0	85,7	0	12	332	300	201	15	127	33	0,020	4281		0%	0%	0%	0%	0%	25%	0%	0%	75%	0%	0%	0%		300	201	
37	10041530	Hefframe	2	0	55,3	0	3	840	1100	221	8	0	28	0,204	271		0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%		1100	221	
38	10041680	Scharnierplaat links	2	0	28,9	0	2	129	275	150	8	89	3	0,005	5431		0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%		275	150	
39	10041690	Scharnierplaat rechts	2	0	28,9	0	2	129	275	150	8	89	3	0,005	5431		0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%		275	150	
40	10041760	HAT-vang	3	0	6,4	0	2	300	75	80	5	0	2	0,002	3556		0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%		75	80	

B.2 Facilities sheet

Removed from the public version

B.3 Allocation of stakeholder 1 for scenario 1



Solve for stakeholder 1

0 = constraint fulfilled
1 = constraint not fulfilled

	Criteria weights			
Stakeholder	Costs	Season	Quality	Lead time
1 Dewulf NL	0,26	0,21	0,31	0,22
2 Dewulf RO	0,65	0,15	0,15	0,05
3 Dewulf BE	0,19	0,19	0,29	0,34
	0,37	0,18	0,25	0,20

				Normalized score								Weighted objective score					Capability constraints		
																	On	On	On
		Productie locatie		Dewulf NL				Dewulf RO									Laser	Bending	Truck
10	Process	Dewulf NL	Dewulf RO	Costs	Season	Quality	Lead time	Costs	Season	Quality	Lead time	Costs	Season	Quality	Lead time	Total	lenght	lenght	dimension
32	10027360	0	1	0,00	0,00	0,00	0,00	10,00	2,75	6,80	7,00	2,6	0,6	2,1	1,5	6,8	0	0	0
33	10027640	0	1	0,00	0,00	0,00	0,00	10,00	2,80	6,80	7,00	2,6	0,6	2,1	1,5	6,8	0	0	0
34	10027780	0	1	0,00	0,00	0,00	0,00	9,00	3,25	6,80	7,00	2,3	0,7	2,1	1,5	6,7	0	0	0
35	10027940	1	0	4,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,0	1,0	2,1	1,8	5,9	0	0	0
36	10027990	0	1	0,00	0,00	0,00	0,00	8,00	1,00	6,80	7,00	2,1	0,2	2,1	1,5	5,9	0	0	0
37	10028080	1	0	4,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,0	1,0	2,1	1,8	5,9	0	0	0
38	10028200	1	0	3,00	7,10	6,90	8,00	0,00	0,00	0,00	0,00	0,8	1,5	2,1	1,8	6,2	0	0	0
39	10029700	0	1	0,00	0,00	0,00	0,00	9,00	2,52	10,00	7,00	2,3	0,5	3,1	1,5	7,5	0	0	0
40	10029860	1	0	4,00	7,10	6,90	8,00	0,00	0,00	0,00	0,00	1,0	1,5	2,1	1,8	6,4	0	0	0
41	10031420	0	1	0,00	0,00	0,00	0,00	10,00	2,74	6,80	7,00	2,6	0,6	2,1	1,5	6,8	0	0	0
42	10032110	0	1	0,00	0,00	0,00	0,00	7,00	4,80	6,80	7,00	1,8	1,0	2,1	1,5	6,5	0	0	0
43	10032170	0	1	0,00	0,00	0,00	0,00	7,00	4,80	6,80	7,00	1,8	1,0	2,1	1,5	6,5	0	0	0
44	10033330	0	1	0,00	0,00	0,00	0,00	9,00	3,25	6,80	7,00	2,3	0,7	2,1	1,5	6,7	0	0	0
45	10041530	1	0	4,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,0	1,0	2,1	1,8	5,9	0	0	0
46	10041680	1	0	4,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,0	1,0	2,1	1,8	5,9	0	0	0
47	10041690	1	0	4,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,0	1,0	2,1	1,8	5,9	0	0	0
48	10041760	1	0	5,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,3	1,0	2,1	1,8	6,2	0	0	0
49	10042280	1	0	4,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,0	1,0	2,1	1,8	5,9	0	0	0
50	10042500	1	0	5,00	4,60	6,90	8,00	0,00	0,00	0,00	0,00	1,3	1,0	2,1	1,8	6,2	0	0	0
51	10050040	0	1	0,00	0,00	0,00	0,00	7,00	8,50	6,80	7,00	1,8	1,8	2,1	1,5	7,3	0	0	0
52	10050050	0	1	0,00	0,00	0,00	0,00	6,00	7,00	6,80	7,00	1,6	1,5	2,1	1,5	6,7	0	0	0
53	10050080	0	1	0,00	0,00	0,00	0,00	6,00	4,00	6,80	7,00	1,6	0,8	2,1	1,5	6,0	0	0	0
54	10050110	0	1	0,00	0,00	0,00	0,00	6,00	4,00	6,80	7,00	1,6	0,8	2,1	1,5	6,0	0	0	0
55	10050640	1	0	5,00	6,26	10,00	8,00	0,00	0,00	0,00	0,00	1,3	1,3	3,1	1,8	7,5	0	0	0
56	10050650	1	0	5,00	6,70	10,00	8,00	0,00	0,00	0,00	0,00	1,3	1,4	3,1	1,8	7,6	0	0	0
57	10052060	1	0	5,00	7,10	6,90	8,00	0,00	0,00	0,00	0,00	1,3	1,5	2,1	1,8	6,7	0	0	0
58	10053410	0	1	0,00	0,00	0,00	0,00	8,00	1,00	6,80	7,00	2,1	0,2	2,1	1,5	5,9	0	0	0
59	10053490	0	1	0,00	0,00	0,00	0,00	10,00	6,85	6,80	7,00	2,6	1,4	2,1	1,5	7,7	0	0	0
60	10053590	0	1	0,00	0,00	0,00	0,00	9,00	4,14	6,80	7,00	2,3	0,9	2,1	1,5	6,9	0	0	0
61	10055620	0	1	0,00	0,00	0,00	0,00	6,00	10,00	10,00	7,00	1,6	2,1	3,1	1,5	8,3	0	0	0
62	10055700	0	1	0,00	0,00	0,00	0,00	6,00	10,00	10,00	7,00	1,6	2,1	3,1	1,5	8,3	0	0	0
63	10057040	0	1	0,00	0,00	0,00	0,00	9,00	5,64	6,80	7,00	2,3	1,2	2,1	1,5	7,2	0	0	0
64	10062930	0	1	0,00	0,00	0,00	0,00	9,00	1,95	6,80	7,00	2,3	0,4	2,1	1,5	6,4	0	0	0
65	10063160	0	1	0,00	0,00	0,00	0,00	10,00	4,00	6,80	7,00	2,6	0,8	2,1	1,5	7,1	0	0	0
66	10067040	0	1	0,00	0,00	0,00	0,00	10,00	3,50	6,80	7,00	2,6	0,7	2,1	1,5	7,0	0	0	0
67	10067870	1	0	10,00	6,04	6,90	8,00	0,00	0,00	0,00	0,00	2,6	1,3	2,1	1,8	7,8	0	0	0

Appendix C – Case study long term graphs

This appendix presents the results of the analysis which are for long-term decision-making. The results are separately presented for each stakeholder group. The first two-bar graphs present the total distribution. The first shows the suggested total distribution of the production processes for each scenario (robot and manual). The second shows the suggested total distribution of the process time for each scenario. The process time shows which percentage of the total welding time of all the processes is performed at the facilities (robot and manual). Next, five line-graphs are presented. Al the Y-axes of the graphs present the number of production processes. The X-axes of each graph are divided into ten equal big categories where the first categories are the smallest 10% values, the second categories are the second smallest 10% values, and so on, until the last categories which are the biggest 10% values. Note that the values of the categories are different for each row of graphs! The different lines in the graphs represent the four scenarios. The legend of all the line-graphs is shown in figure C.1. The first to line graphs show the distribution of production processes based on the process time. The third line-graphs show the distribution of production processes based on the size of the assemblies. The last two line-graphs shown the distribution of production processes based on the welding time per cubic meter of the assembly. The last bar-graph shows the total costs for each scenario. The total costs are shown for the current situation (all Dewulf NL), a situation where all processes are performed at Dewulf RO (all Dewulf RO), and the suggested allocation according the stakeholders. All the results of the appendix are discussed in section 5.3.8, accordingly conclusions and recommendations about the results are presented in section 5.4.

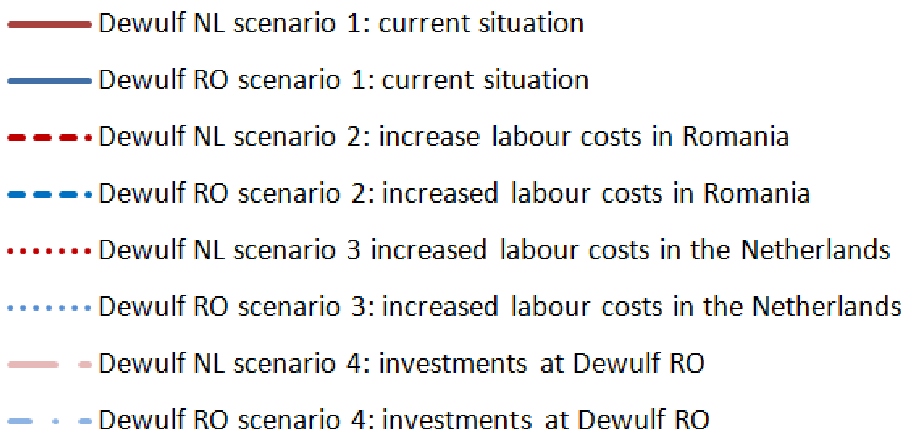
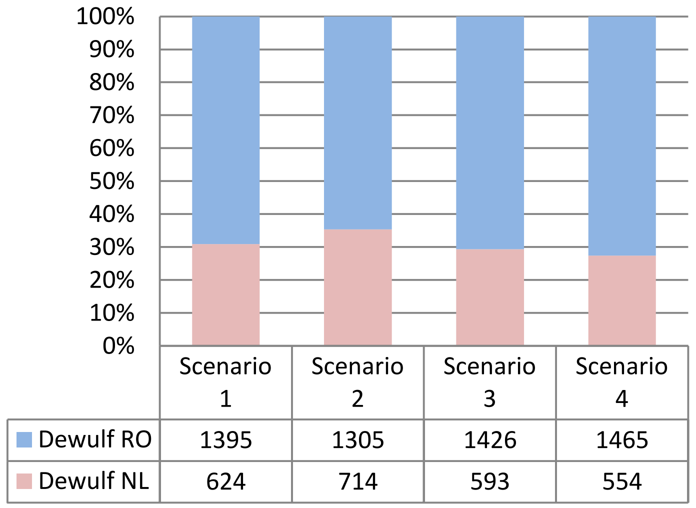
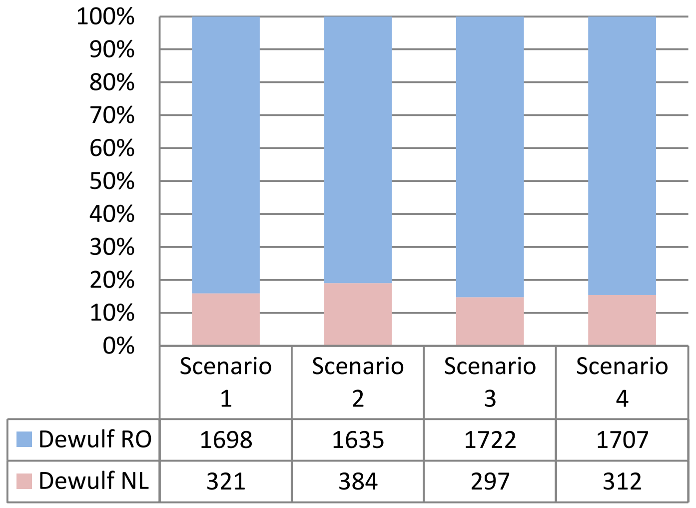
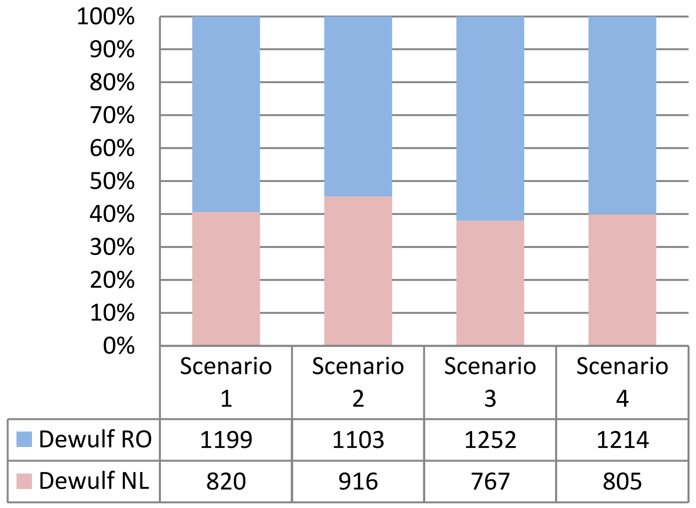
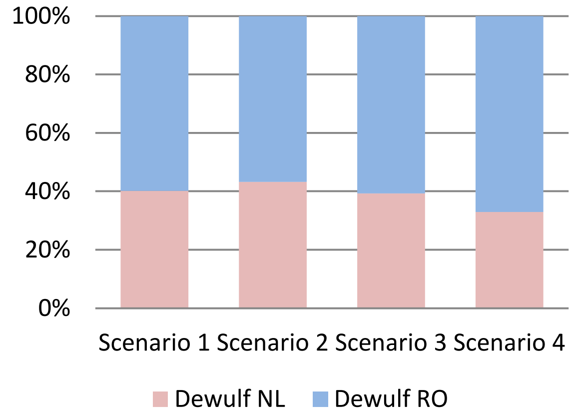
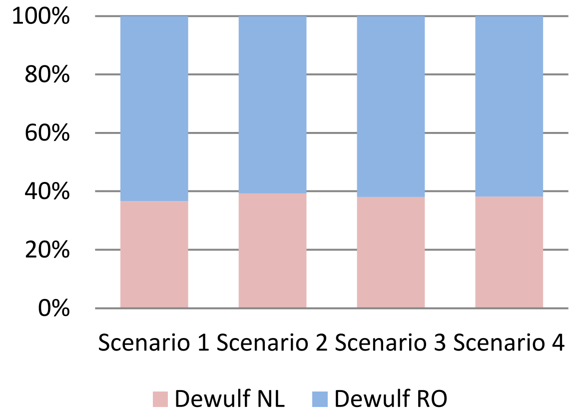
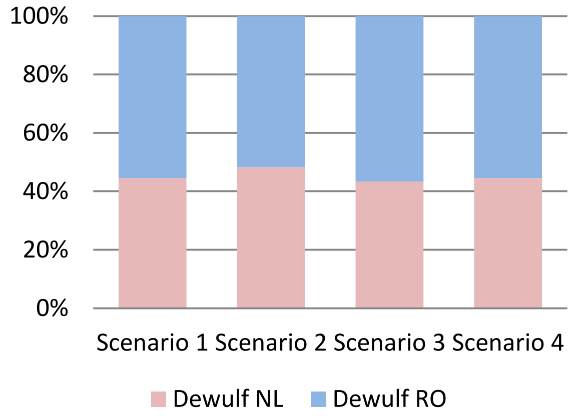


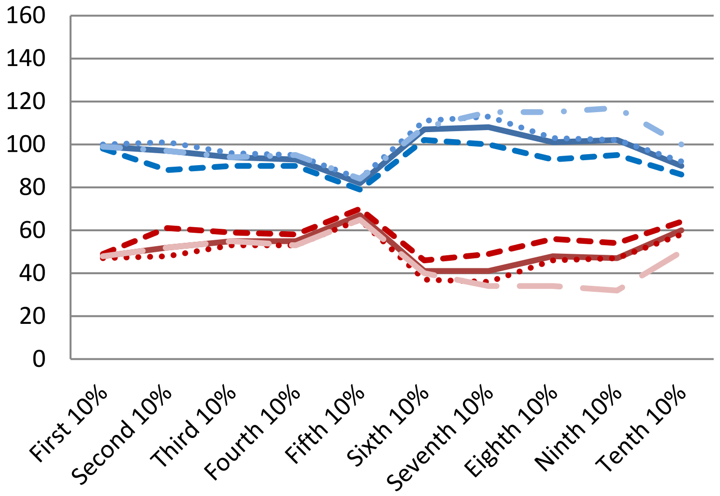
Figure C. 1: legend for all the line graphs

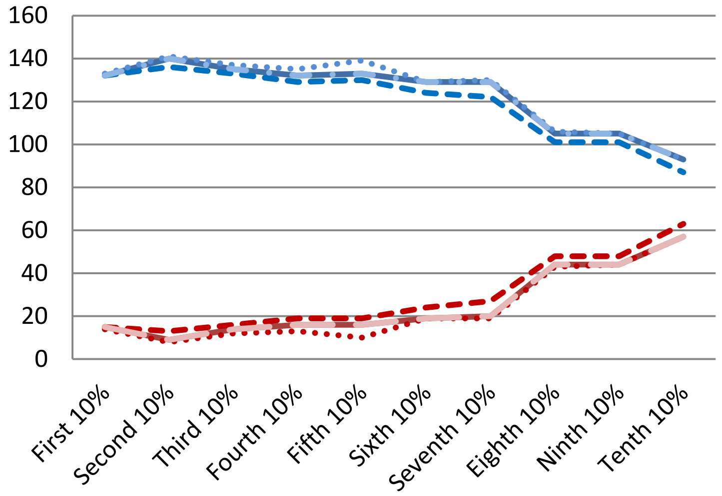
Table C. 1: Distribution graphs

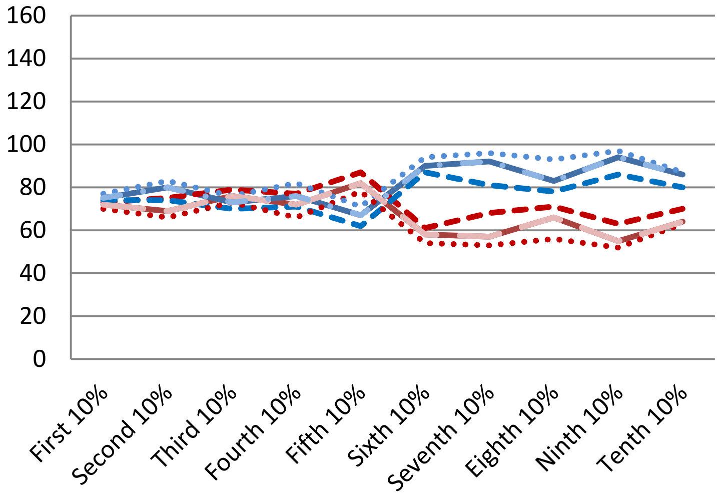
	Stakeholder 1: Dewulf NL	**Stakeholder 2: Dewulf RO**	**Stakeholder 3: Dewulf BE**
Total distribution of processes			
Total distribution of process time			

Distribution welding processes based on Manual process time

(first 10% is shortest processes, last 10% are the longest processes)

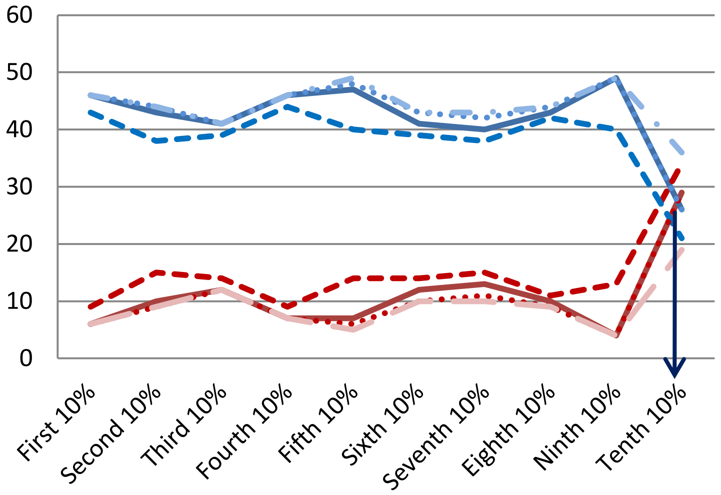


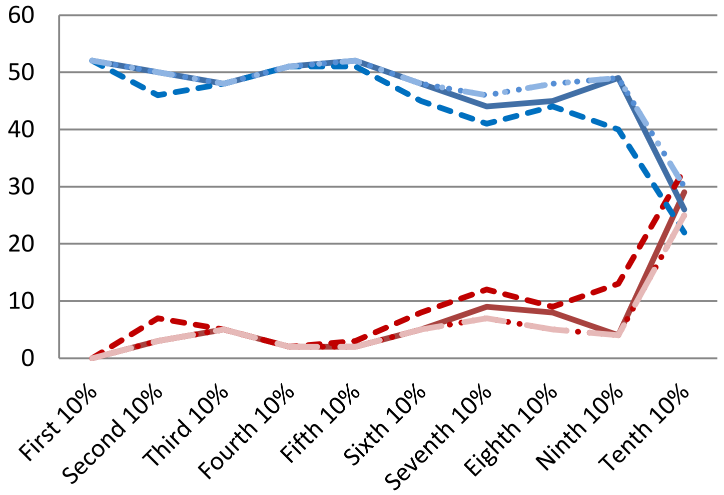


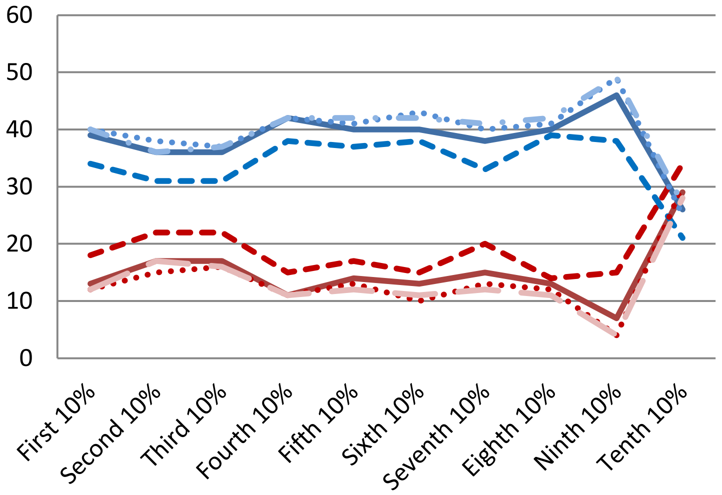


Robot process time

(first 10% are the shortest processes, last 10% are longest processes)

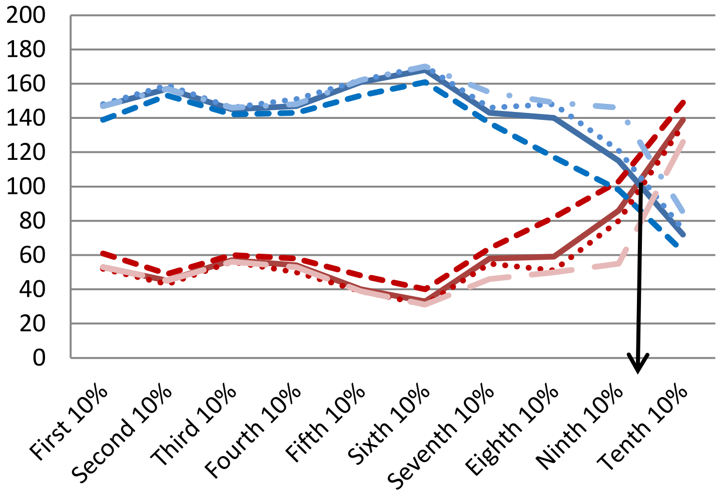


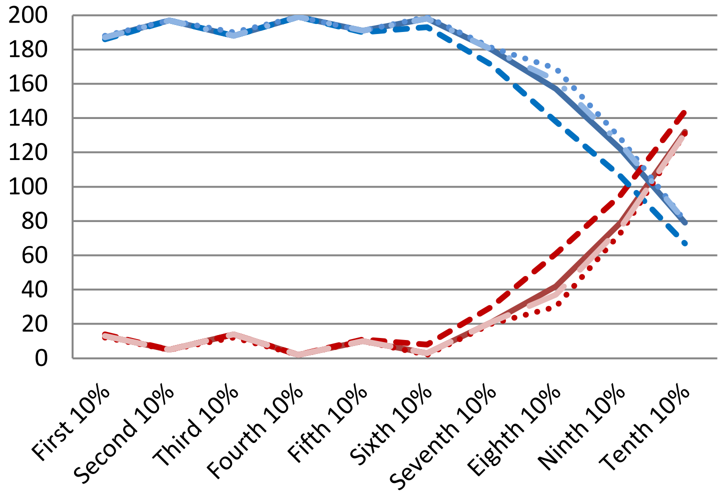


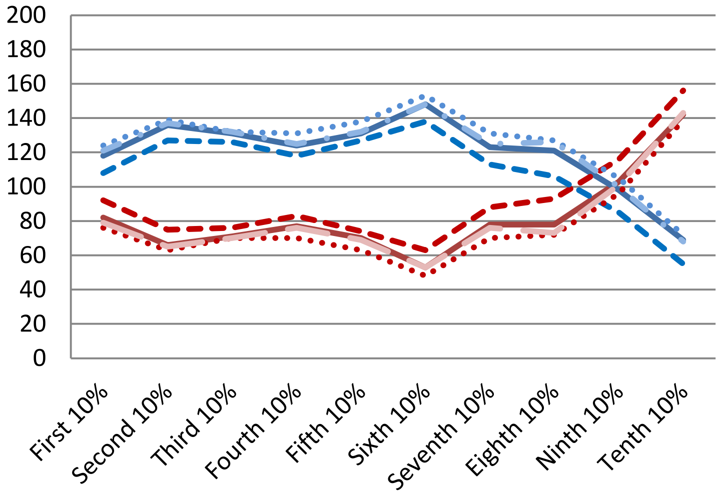


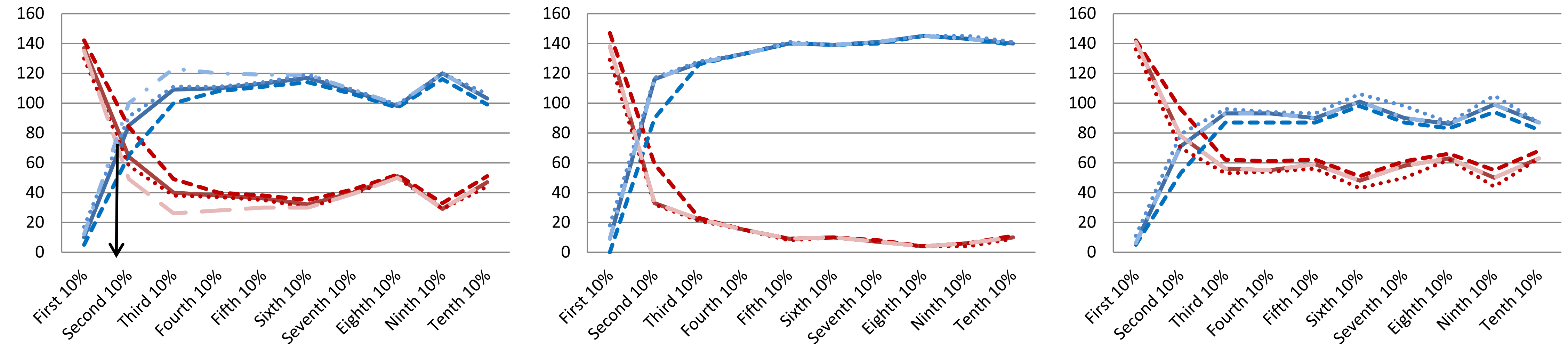
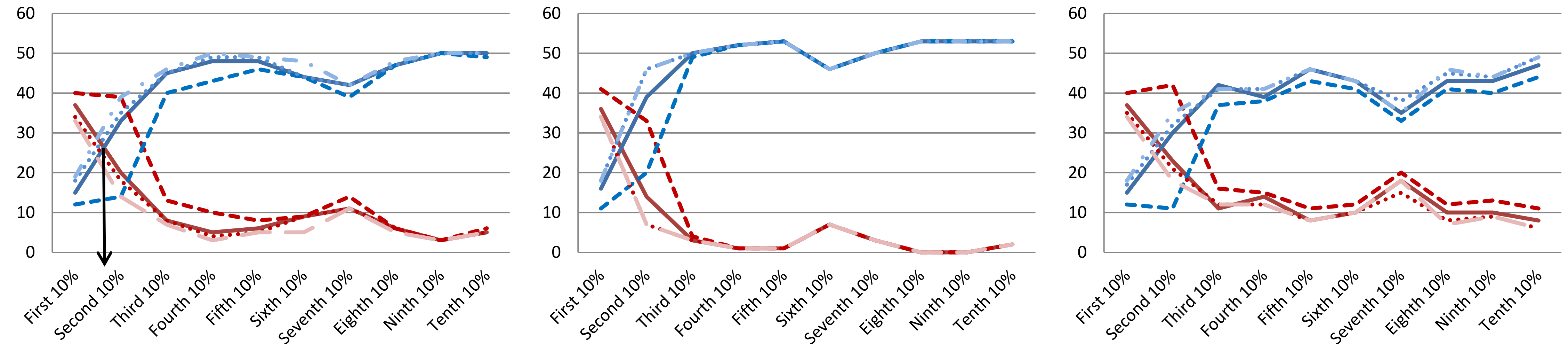
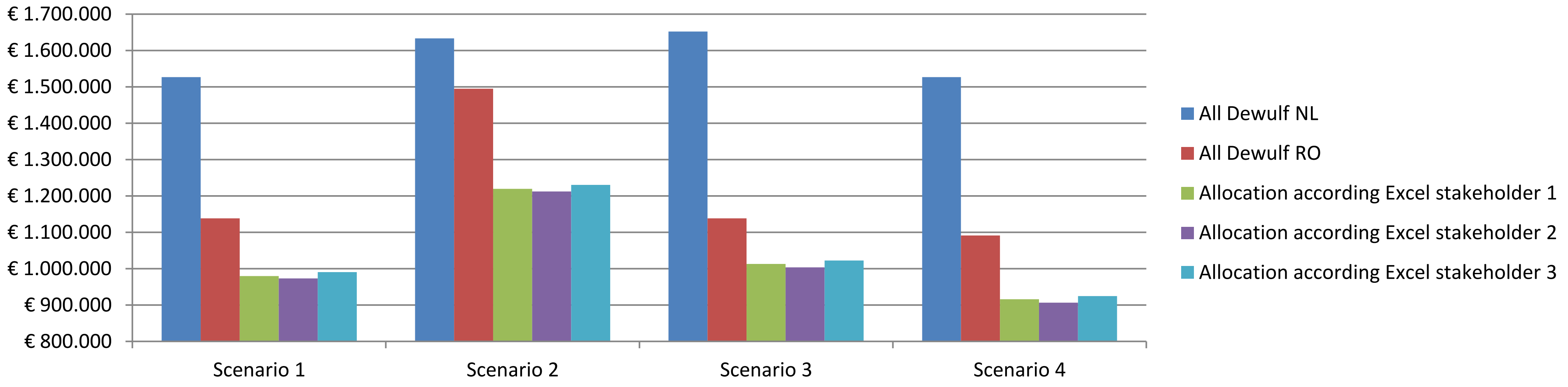
Assembly dimensions

(first 10% are the smallest assemblies, last 10% are the biggest assemblies)

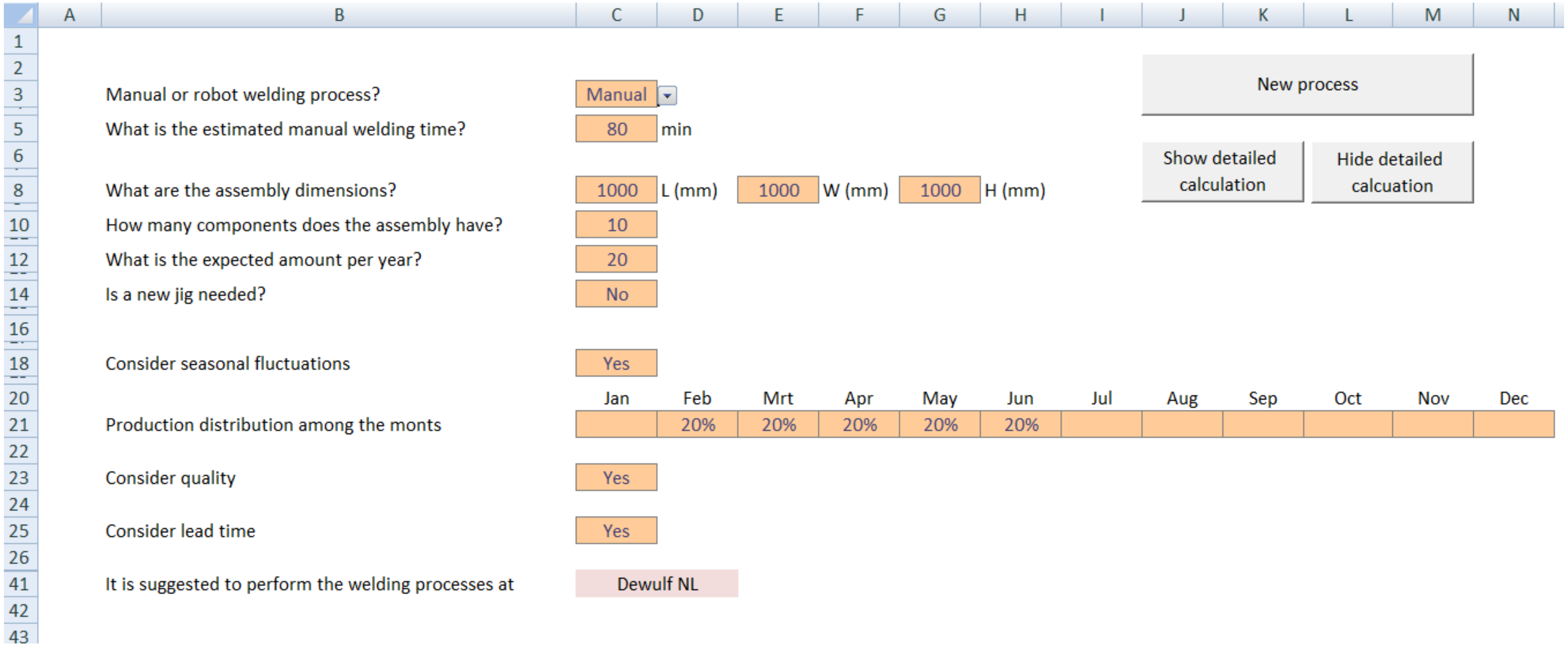






Manual welding time per cubic meter (first 10% are the assemblies with the lowest welding time per cubic meter, last 10% are the assemblies with the highest welding time per cubic meter)	
Robot welding time per cubic meter (first 10% are the assemblies with the lowest welding time per cubic meter, last 10% are the assemblies with the highest welding time per cubic meter)	
Total costs	

Appendix D – Short-term decision support tool



Manual or robot welding process? Manual

What is the estimated manual welding time? 80 min

What are the assembly dimensions? 1000 L (mm) 1000 W (mm) 1000 H (mm)

How many components does the assembly have? 10

What is the expected amount per year? 20

Is a new jig needed? No

Consider seasonal fluctuations Yes

	Jan	Feb	Mrt	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Production distribution among the monts		20%	20%	20%	20%	20%						

Consider quality Yes

Consider lead time Yes

It is suggested to perform the welding processes at Dewulf NL

Figure D. 1: Short-term decision support tool