Master Thesis

Industrial Engineering and Management

Robust production planning at DIPP with re-scheduling after disruptions

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UNIVERSITY OF TWENTE.

DEMCON

Preface

Dear reader,

You are about to read the master thesis 'Robust production planning at DIPP with re-scheduling after disruptions', the result of my research to finalize the Master of Industrial Engineering and Management. This research was conducted at DIPP, a sub-company of Demcon located in Enschede, the Netherlands.

At DIPP, I learned much about the reality of production planning compared to the theory I studied at the University of Twente. Besides practical insights relevant to my thesis, I will also remember the days I was allowed to help test the produced machines. I want to thank the entire DIPP team for assisting me in the creation of this thesis. A special thanks to my supervisor at DIPP, Sharon Boogert, who helped me whenever I got stuck and guided me throughout the entire thesis.

I also want to thank my first supervisor, Engin Topan, for his time and effort. I enjoyed our meetings, which helped me improve my thesis further. I would also like to thank my second supervisor, Derya Demirtas, who provided new insight into my thesis, helping me improve it further in the final stages.

This master's thesis marks the end of my studies and student life. I am very grateful for my time at the University of Twente and the many exciting experiences that have helped me develop myself further. During my time here, I found my passion for logistics in all kinds of areas and for organising events, of which especially the organisation of the introduction period, the Kick-In, was a fantastic addition to my student life. Furthermore, I have made many great friends here, and I would like to thank them and my family for their support while writing this thesis. A special thanks to Wouter, who always cheered and supported me when I needed it.

Enjoy reading this thesis!

Carlijn Meijerink

Enschede, November 2024

Management Summary

This research was conducted at DIPP, a sub-company of Demcon located in Enschede, the Netherlands. DIPP is a production company founded to extend Demcon's capabilities towards large machine production. The products produced at DIPP have never been produced before or only in small batches. During the past production projects at DIPP, many disruptions occurred during production, increasing the labour hour budget by 45 percent. The selected core problem of this thesis is the inability of the current production plan to deal with disruptions without increasing the labour hour budget. This research aims to provide DIPP with insight into the disruptions that affect a production plan and advice on how to be more robust against them. Therefore, this research answers the following research question:

'How can DIPP improve their current production planning method to be more robust against disruptions such that the production projects stay within their set labour budget?'

The products produced at DIPP are split into several production activities, each with its labour hour estimate and material lead-time estimate. Many disruptions can affect the production of these activities; however, in this thesis, the disruptions are classified into two categories: a change in a production activity's start date by extending the material lead time or a change in the labour hours needed for a particular activity. Currently, DIPP's production planning method does not assist the project manager in creating robustness against these disruptions.

The literature research selects a proactive-reactive modelling approach to creating and updating a production plan. The proactive approach assists the project manager in developing a plan without knowledge of future disruptions. A deterministic model, using the Resource Constraint Project Scheduling Problem (RCPSP) as a basis, is created that minimises the project's makespan and labour hour-level variations. The model can incorporate two types of slack against disruptions: slack in labour hours (H) or slack in a material's lead time (L). A multiplication factor of the original labour hour or material lead time estimate determines the amount of slack. The reactive approach assists the project manager to reschedule within a production plan when a disruption occurs. The proactive model is therefore adapted so that the effect of the disruptions can be incorporated and the needed overtime and changes to the initial plan are minimised.

The amount and placement of slack incorporated in the proactive plan affect the plan's robustness against random disruptions. Three placement policies for labour hour slack are tested: equal division of slack over the production activities, division of slack based on its average demand for a set amount of disruptions, and placement of slack at the end of the production project. The labour hour policies and material lead time slack factors are tested against randomly generated disruptions. These disruptions are based on the distribution of past disruptions data and indicate that labour hour disruptions can have a multiplication factor of the original estimate between 0.4 and 1.8. The peak of labour hour disruptions lies at a factor of 1.3. Similarly, the range is established for lead time disruptions from 0.6 to 1.9, peaking at 1.3. The number of disruptions tested goes from 0 to three times the number of production activities of a project. Two factors measure the performance of slack against disruptions: the additional labour hours needed and the amount of hours that end up unused. Lead time disruptions can create unused hours by postponing the start of production and not using the initially planned hours. The scenarios are compared by their total costs, using a rate of 100 euros for initial hours, 124 euros for the first two hours of overtime and 141 for additional overtime.

The placement of slack is evaluated in six scenarios. These test the sensitivity of hour and lead time slack against their corresponding disruptions and provide insight into the practical use of slack in realistic production planning settings. These scenarios were created using data from the assembly of two production projects at DIPP. The first production project is a small project containing ten production activities and has an assembly time of two weeks. The second production project is a large project consisting of 43 different production activities and takes about seven weeks.

In addition to the experiments, a tool to improve production planning in the future has been built to allow the DIPP project manager to work with the created models. The tool creates a production plan based on provided information on production projects, allows for optimal rescheduling after a disruption within the boundaries of the initial planning, and provides the option to download the created plan to Excel.

Based on the experiments conducted and insight gained from this thesis, the following conclusions are provided:

- Labour hour and material lead time slack are effective against their corresponding disruptions when tested independently. A slack factor equal to the average factor of hour disruptions, 1.3, is enough for the hour slack to be robust against the entire range of disruptions. For lead time slack, a slack factor at the end of the lead time range, 1.8, is needed to be robust against the entire range of lead time disruptions.
- The use of hour slack with a lead time slack factor on the lower side works counterproductive as the additional labour hours end up unused because of the many lead time disruptions. Therefore, hour slack should only be used when there are little lead time disruptions or when a high lead time slack factor is used.
- Equal slack placement over all production activities works better than proactively determining slack. The proactively created planning does not produce a realistic production plan, and the total costs are not lower than when equal slack is placed. Equal slack also performs better than slack when placed at the end of a production plan. This is because the experiments disrupt the production plan before production starts. Therefore, equal slack can incorporate the disruptions in the plan without changing the planned activities in a week. Regarding slack placed at the end, the activities need to be moved to further weeks, which our model penalises.
- For the current production projects, a trade-off is found between lower production costs and postponement of the production plan. The low costs mean the labour hour budget has not increased much, representing the best-performing slack factor cases. The trade-off for both projects is visualized in Figure 1 and 2.
- The multi-project scenarios in this thesis did not indicate a decrease in average costs per project when the incorporated slack is shared.

	Average costs over all disruption amounts	Week																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Original planning	€ 23,339											59	59								
(H = 0, L = 1.1)	€ 22,033												59	59							
(H = 0, L = 1.2)	€ 20,493													59	59						
(H = 0, L = 1.3)	€ 18,542														59	59					
(H = 0, L = 1.4)	€ 16,288															59	59				
(H = 1.0, L = 1.5)	€ 15,725															65	65				
(H = 0, L = 1.6)	€ 15,058																59	59			

Figure 1: Trade-off for production project 1 between duration and hours of initial production plans and their average total costs over the disruption range (0-30), incorporating various levels of labour hour (H) and lead time (L) slack.

	Average costs over all disruption amounts	Week																									
		1 to 25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Original planning	€ 333,478				251	251	251	251	251	251	251																
(H = 1.0, L = 1.1)	€ 302,028							251	251	251	251	251	251	251													
(H = 1.2, L = 1.2)	€ 280,716									301	301	301	301	301	301	301											
(H = 1.1, L = 1.3)	€ 264,508											276	276	276	276	276	276	276									
(H = 1.1, L = 1.4)	€ 235,258														276	276	276	276	276	276	276						
(H = 1.2, L = 1.5)	€ 179,443																301	301	301	301	301	301	301				
(H = 1.1, L = 1.6)	€ 190,902																		276	276	276	276	276	276	276		

Figure 2: Trade-off for production project 2 between duration and hours of initial production plans and their average total costs over the disruption range (0-120), incorporating various levels of labour hour (H) and lead time (L) slack.

Based on the conclusions and the knowledge gained from this research, we provide DIPP with the following recommendations:

1. Only incorporate a slack in labour hours when the plan is robust against lead time disruptions.
2. When hour slack is incorporated, spread it equally over all production weeks and use the created tool to use the additional hours optimally when a disruption occurs.
3. Use the created trade-off between total production costs and completion of production projects 1 and 2 to determine their future production plans.
4. Collect data on the range and distribution of future disruptions to improve the knowledge of the required slack.

Contents

List of Abbreviations

Abbreviation	Description
AoN	Activity on the Node
ATO	Assemble to Order
BOM	Bill of Materials
CODP	Customer Order Decoupling Point
ETO	Engineer to Order
GUI	Graphical User Interface
MTO	Make to Order
MTS	Make to Stock
PS	Project Scheduling
RCCP	Rough-Cut Capacity Planning
RCPSP	Resource Constraint Project Scheduling Problem
WIP	Work In Progress

Table 1: List of Abbreviations

1 Introduction

This master's thesis is conducted at DIPP. The focus of the research is on improving production planning at DIPP. Section 1.1 introduces the reader to the company. The motivation for the study is given in Section 1.2. The research problem is described in Section 1.3. Section 1.4 describes the research design.

1.1 Company Description

1.1.1 Placement of DIPP within Demcon

DIPP is a sub-company of the larger mother company, Demcon, located in Enschede, the Netherlands. Demcon was founded in 1993 and has grown to 1100 employees and nine locations, spread over four countries. Demcon's headquarters are located in Enschede, the Netherlands. Demcon works on creating solutions in the areas of aerospace, agri & food, defence & security, energy, high-tech systems & materials, life sciences & health, smart industry and water & maritime. Demcon consists of 25 companies that work on these topics, of which Demcon Production is one (Demcon, 2024). Demcon Production can also be split into sub-companies, of which DIPP is one. The placement of DIPP within Demcon is visualized in Figure 3

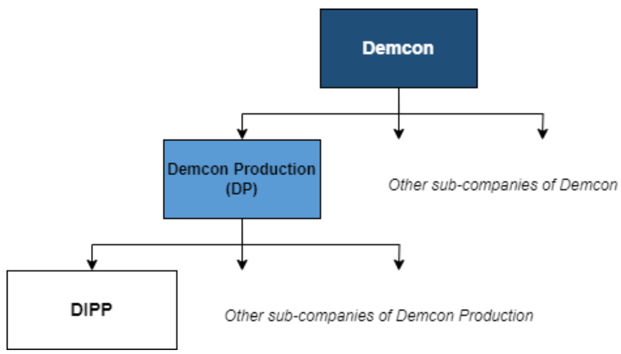


Figure 3: Placement of DIPP within Demcon's company structure

1.1.2 DIPP

DIPP was founded at the start of 2023 to extend Demcon's focus towards larger machine production, which was impossible at the current Demcon Production location (Production, 2024). DIPP has a separate production hall with space to produce three to four larger machines simultaneously. Currently, DIPP has completed two machines, both for the same client. Furthermore, they recently acquired another client of which production is running. So far, the products brought to DIPP have been designed by other Demcon companies and built only a few times, of which most are considered prototypes. DIPP's goal is to get the newly designed product to production. However, starting up a new production project means a lot of uncertainty regarding the design's production times, materials and feasibility. Each production project is also split into multiple activities, which must be executed in a particular order. Therefore, a disruption in an activity early in the production project might also affect other activities later.

1.2 Motivation for Research

This section describes the motivation for this research. As mentioned in section 1.1.2, DIPP has to deal with a lot of uncertainty during machine production. Many factors can cause uncertainty; this could be an underestimation of the needed production hours or a request from a client to change the design. The machines produced at DIPP follow a project-based approach, meaning each machine is treated as a separate project. The project's budget has increased regarding costs and time for the two machines already produced. Consequently, DIPP is interested in enhancing its current production planning method to improve reliability and meet the client's expectations more effectively.

Furthermore, DIPP is extending its client base, and with the production of more machines, the complexity of managing multiple production projects simultaneously will increase. Production capacity must be allocated to several projects efficiently to avoid delays and cost overruns. Next, the effect of changes to the production plan on production planning must be clear to track possible delays and cost overruns.

1.3 Research problem

This section describes how the specific research problem has been formulated and creates a better understanding of the context. The problem has been defined using the methodology of (Heerkens and Winden, 2017). First, the action problem is described, then the problem cluster is explained, and lastly, the core problem is selected.

1.3.1 Action problem

An action problem is the discrepancy between the norm and reality perceived by the problem owner (Heerkens and Winden, 2017). The problem owner, DIPP, noticed that the budgets had been increased in terms of time and cost for the two completed production projects. Specifically for labour hours, a lot more were used than initially anticipated, which caused the deadline to be exceeded and resulted in higher labour costs. The labour budget has increased by 45 per cent for both projects. Therefore, the action problem can be described as follows:

The production projects at DIPP increased the labour budget by 45 per cent.

1.3.2 Problem identification

A problem cluster is created to visualize the connections between the action problem and related problems. The associated issues have been derived by observation and interviewing internal stakeholders. The problem cluster can identify potential core problems, as seen in Figure 4.

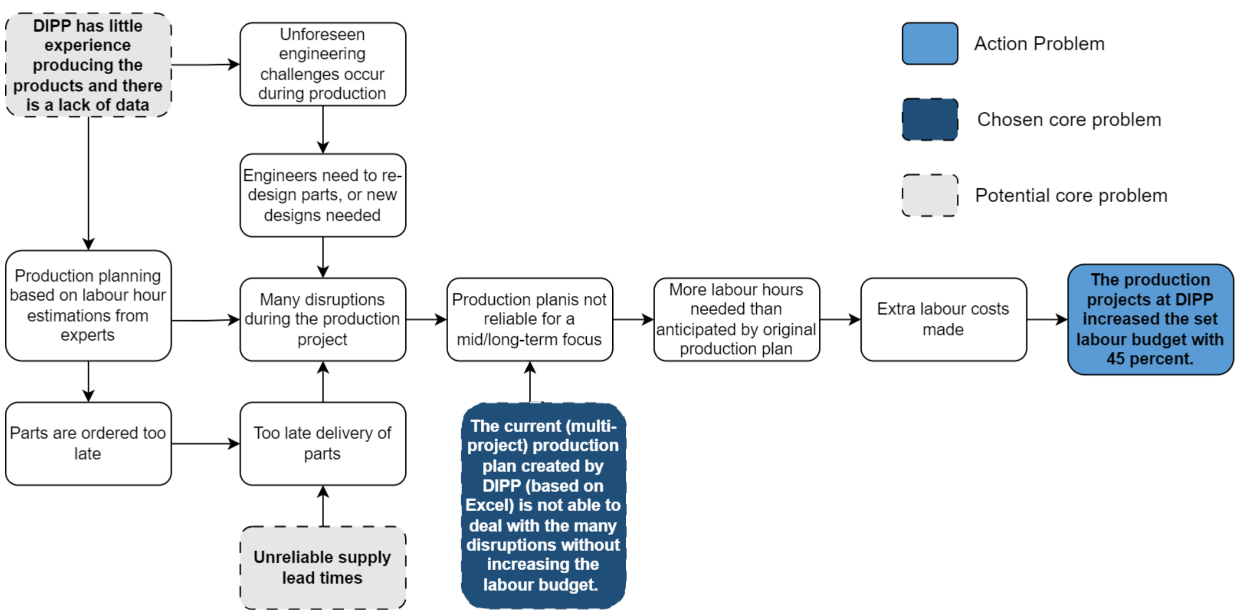


Figure 4: Problem Cluster DIPP

The action problem, 'The production projects at DIPP increase the labour budget by 45 percent', is a consequence of more labour hours and, thus, costs being needed than initially anticipated. The required labour hours for a production project were estimated at the start of the project and did not turn out to be reliable. During the production project, many disruptions happened that were not anticipated by this planning. The disruptions can have three main causes.

The first cause is that the parts needed for production arrive too late. This way, the completion of a production activity must be postponed until the part has arrived. There are two reasons for the arrival being too late. First, the parts can be ordered too late, either by the purchasing department or the order has been passed too late from the project manager to the purchaser. This could be because the time needed to order and receive parts has been estimated optimistically. Secondly, the supply lead times can be unreliable. This, for some part in the past projects, was caused by the effects of the pandemic, but also because not all the suppliers have a reliable lead time.

A second reason is that the engineers need to re-design certain parts. A re-design can be required in several cases. This can be because parts do not fit together as they are supposed to during production or because, during testing, a product does not function as expected by DIPP or the client.

A third reason is that the time needed to produce a product or to perform testing is estimated by experts rather than based on data. These estimations are based on the product's technical design files, and while the experts are very familiar with such files, the estimations might be too high or low.

Next to the three direct causes of the many production disruptions, a more general underlying problem is DIPP's little experience with machine production. Since the machines are newly designed and only a few (prototype) machines have been built, there is no previous data on the duration of production.

1.3.3 Core problem and motivation

The problem cluster in Figure 4 identifies three problems which don't have an underlying cause and can therefore be considered a core problem. This section discusses these core problems and evaluates if they can be influenced and selected as a research topic (Heerkens and Winden, 2017). The first core problem is that DIPP has little experience producing the products and lacks data regarding the production time needed. Since DIPP was founded at the start of 2023 and has only completed two production projects, there has not been much opportunity to gather experience. Furthermore, each newly designed product will start without data on the specific hours needed for production. While this problem has influenced past projects a lot, the lack of experience cannot be influenced without producing more of the same machines. Therefore, this problem is not considered as the core problem of this research.

A second core problem is the unreliability of supply lead times. During the past two production projects at DIPP, an issue that often occurred was the late arrival of parts. The purchasing department indicated that supply chain disruptions during the pandemic partially caused this and that most lead times have decreased or become more reliable. However, they also stated that suppliers still have uncertain lead times. This uncertainty cannot be influenced as it is an external source, but the unreliability of lead times can still be considered for this research.

The third and last core problem is that the current production planning created by DIPP cannot deal with the many disruptions without increasing the labour budget. While disruptions are unforeseen, the planning can be improved by considering possible disruptions and efficiently rescheduling after a disruption. This problem can, therefore, be influenced and is chosen as the core problem to solve during this research. The core problem is formulated below:

The current production planning created by DIPP, based on Excel, cannot deal with the many disruptions without increasing the labour budget.

1.4 Research Design

The research is designed based on the methodology of (Heerkens and Winden, 2017). Their methodology comprises seven distinct steps: Defining the problem, formulating the approach, analysing the situation, formulating (alternative) solutions, choosing a solution, and implementing and evaluating it. These steps are the guidelines for the formulation of the research questions. First, the research questions and their approach are explained. Next, the scope and stakeholders are identified, and the chapter closes with the deliverables and a timeline.

1.4.1 Research questions

Based on the identification of the core problem, the main research question has been formulated as follows:

'How can DIPP improve their current production planning method to be more robust against disruptions such that the production projects stay within their set labour budget?'

The following sub-questions have been defined to answer the research questions. The motivation and approach for each question are specified.

1. *What is the current production planning method at DIPP?*
    - What products are produced at DIPP?
    - What aspects of products overlap and can, therefore, be used to generalize a product at DIPP?
    - How is the current production plan created?
    - How is the current labour hour estimation made, and what costs are involved?
    - What are common disruptions during production, and how does DIPP deal with them?

    The first research question will be answered by interviewing stakeholders and studying data on past production projects. This question will describe the context of the research in detail.

2. *Which methods are presented in the literature to create a robust production plan?*
    - How can the problem at DIPP be classified in literature?
    - What robust (multi-project) production planning methods are available in the literature, and can they be used for labour planning and/or scheduling?
    - What project re-scheduling methods are suitable to use after a disruption?

    The second research question will try to relate DIPP's problem to other problems in the literature. It aims to find relevant models in the literature that could be used at DIPP to improve their project planning method. Next, suitable methods to re-plan a project after a disruption should also be selected.

3. *How should the robust production planning model be designed?*
    - What are the requirements and assumptions to be considered in the model?
    - What input data is needed, and how should it be designed keeping future projects in mind?
    - What should the output of the planning look like?
    - How can the model be formulated?

    The third research question uses the knowledge gained on suitable models from the literature research in question 2 and creates a problem-specific model.

4. *How can the designed modelling approach be evaluated and validated?*
    - Can the model be considered valid?
    - How can the performance of the designed model be assessed?
    - What insights does the model give regarding robust project planning?

    The fourth research question selects a methodology to assess the performance of the designed model and concludes its performance. The validity of the model is also evaluated.

5. *How can the model be implemented and maintained at DIPP?*
    - How can the stakeholders implement the model?
    - How can the model be extended and maintained in the future?

    The fifth research question describes the implementation of the DIPP model and how to maintain and extend it.

6. *What recommendations and conclusions should be given to DIPP based on this research?*
    - What are the main recommendations of the conducted research?
    - What are the limitations of the conducted research?
    - What are the main conclusions of the conducted research?

The sixth research question provides DIPP with recommendations and conclusions based on this research. It also discusses the limitations of the study.

The research questions are answered in the different chapters of this research. The approach per chapter can be described in the flowchart in Figure 5.

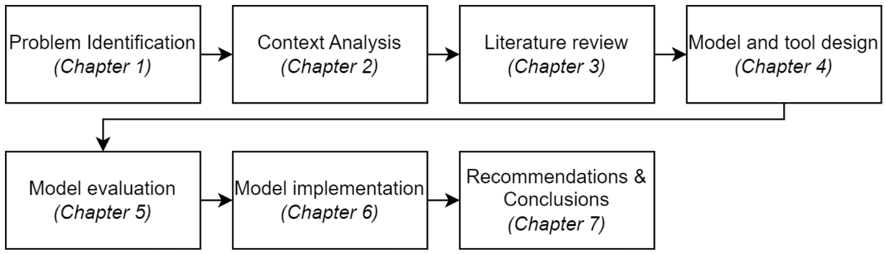


Figure 5: Research flow of this thesis per chapter

1.4.2 Scope

The production environment at DIPP has to deal with a lot of uncertainties. To provide concrete research and to stay within the time boundaries set by the University, the study will be performed within a specific scope. By defining the action and core problem in section 1.3.2, the research focus has been narrowed to production planning at DIPP. It aims to provide a more robust production plan that optimises under disruptions and lets projects stay within the set labour budget. Considering disruptions, two main categories have been defined that will be considered. In Chapter 2, the specific disruptions that fall within these categories will be described.

- A change in the production *labour hours* needed for a production activity.
- A change in a production activity's earliest *start time*, defined by their longest material lead time.

1.4.3 Stakeholders

The primary stakeholder is DIPP. Within DIPP, the project manager is the key stakeholder for this research.

1.4.4 Deliverables

After the completion of this thesis, the following deliverables will be handed over to DIPP:

- A tool that assists DIPP in creating robust production plans.
- A manual for the tool.
- This master thesis to understand how the research has been conducted.
- Recommendations and conclusions regarding robust production planning at DIPP.

2 Current Situation

This chapter describes the current situation regarding production planning at DIPP. Therefore, the following research question is answered in this chapter:

What is the current production planning method at DIPP?

First, this chapter provides relevant context by describing the production projects that have run or are running at DIPP, after which a generalization of the projects is made. Then, the chapter describes the current project planning process, including determining the needed labour hours and incorporating material lead times. Lastly, it discusses the types of disruption during production and the approaches taken in past projects.

2.1 Production projects at DIPP

So far, two different products have been built at DIPP. One is currently being built, here called production project 1, and another has been built twice, called production project 2. The products will be explained in more detail, but first, the context for the term production projects is given, as these terms will be used throughout this thesis.

The production plan at DIPP consists of one or multiple production projects running sequentially or in parallel. Each production project contains the production of one product. A production project consists of multiple production activities, which can consider the assembly of a specific part of a product or the testing of a product. The activities must be executed in a set order.

2.1.1 Production project 1

The currently running production project at DIPP is relatively small. The product being built is a machine used for material production. Assembly of production project one is split into ten production activities, totalling 118 hours, which take about two weeks to complete.

2.1.2 Production project 2

The product built in the past is a larger project, and the results also initiated the reason for this thesis. The product built is a machine relevant to the agri & food field. The product comprises different sections that work together but can be built separately. Two of the three sections are produced at DIPP. Production project two is split into 43 assembly activities, totalling 1754 hours, which have taken multiple weeks to months to complete. The design of product 2 was done by another Demcon company, called DIS, located in Groningen. The first two iterations of the products were built there, both considered prototypes, and the third and fourth iterations were produced at DIPP.

2.2 Generalization of machines

The products produced at DIPP need to be generalized to work with multiple production projects in a model. This section describes aspects that are similar between the two production projects.

The machines produced at DIPP are divided into several production activities, which can be executed separately from each other and then integrated and tested at the required stages. The activities need to be executed according to several precedence relations. The configuration engineer determines which parts of the machines need to be completed before an integration or test can occur. Production projects 1 and 2 consist of 10 and 43 activities, respectively, whose order is determined by precedence relations. Furthermore, a labour hour estimate is made for each activity, and the longest lead times per product are used to decide when the production project can start.

Based on the products currently produced by DIPP, the following generalizations of a production project can be made. This generalization will most likely also apply to future products:

1. The production project consists of several (sub-) activities which should be executed according to their precedence relations.
2. For each (sub-) activity, a labour hour estimation is made.

3. For each (sub-) activity, a lead time (estimation) for the materials is made of which the longest one can be used to determine the activity's start time.

2.3 The current production planning process

The project manager creates the current production plan. The exact steps for the creation are specified below, as well as the currently used tool.

2.3.1 Creation of the production planning

The following steps summarize the creation of the production planning:

1. The client places a request for the production of a machine and provides a deadline.
2. Experts on the topic estimate the number of hours needed for the machine production, looking at the technical files provided. Possible risks, such as if a material might be delivered later or the technicality of the modules, are taken into account.
3. Based on the estimated hours, the project manager creates a high-level project plan specifying only large steps such as 'purchasing', 'assembly' and 'testing' and draws up the quotation.
4. Once the quotation is accepted, the needed materials can be purchased and the capacity is requested.
5. The production planning is specified in more detail, including the activities that must be completed each week.

When production starts, the project manager meets with the assembly coordinator once a week or more if needed. In these meetings, the planning for the coming 2-4 weeks is discussed, and planning changes are made based on the currently achieved results. In this meeting, disruptions that have occurred or will most likely happen, such as the delay of parts or change requests by the client, are also considered. After the plan is adapted, the assembly coordinator assigns the determined weekly tasks to the specific mechanics and engineers. The production team works according to the agile principle, so the task division is done during a (daily) stand-up.

The flow of the current planning process is illustrated in Figure 6. This thesis will focus on two of the stages. First, the 'General planning is done by the project manager, and the quotation is drawn up' to provide insight into how many hours are needed to complete the production projects. Secondly, the phrase, 'planning is updated based on current status', by assisting in using the planned labour hours optimally.

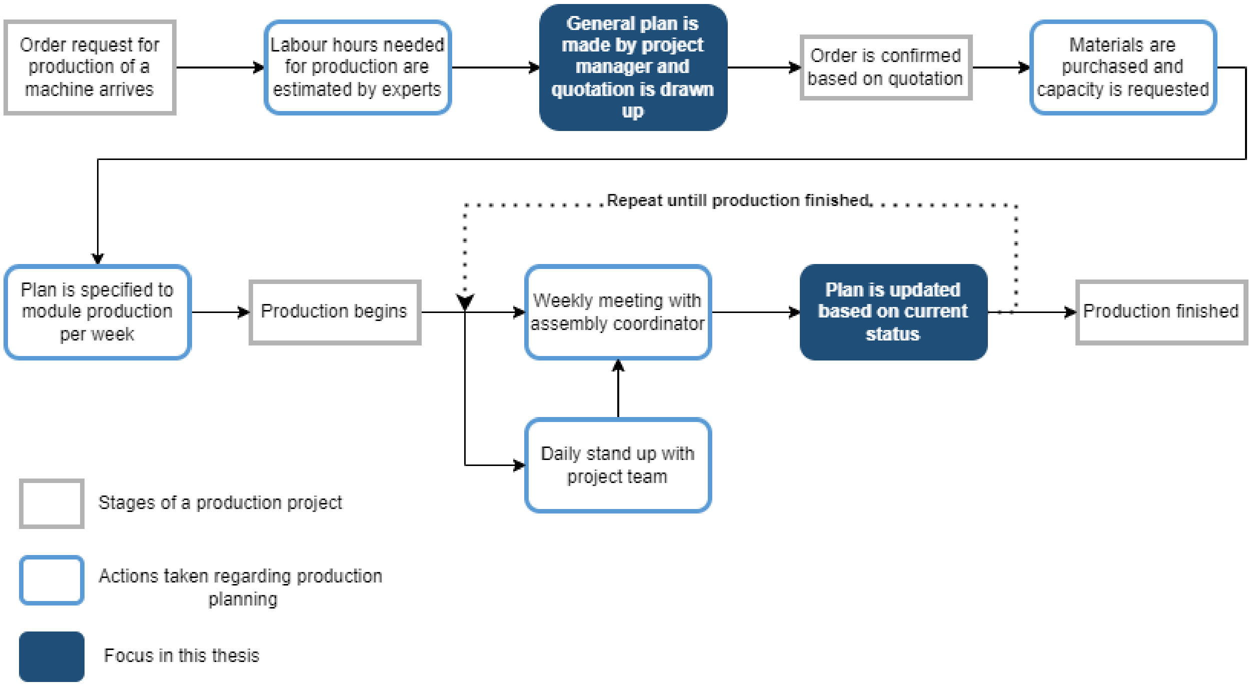


Figure 6: Flow of production plan creation and adaptation

The determined labour hours for the quotation and the specified production planning result in a needed labour hour capacity over the chosen production weeks. The project manager can arrange this labour capacity within the DIPP team, but it can also be requested by other Demcon companies if asked enough in advance. The costs for a labour hour depend on the team and the type of mechanics and engineers needed. When the arranged labour capacity does not turn out to be sufficient during production, the need for overtime can arise. While in practice, not every overtime hour is billed, as it can be compensated by letting an employee work less at other times in the week/month, for the sake of consistency in this thesis, the costs of overtime are aligned with the percentages agreed upon in the DIPP collective employee agreement. Table 2 shows the employee costs per project used in this thesis. They do not represent the actual cost but are in the same order of magnitude. The regular cost for production project 2 has been set at 100. The other costs in the table have been calculated based on their proportions to this cost. When arranging a production team, it can happen that there are not enough employees available. In this case, the project manager can decide to hire external employees for the project's duration; external employees' costs are roughly twice as high as those of internal DIPP employees. While this does happen in practice, the scope of hiring external employees is beyond the production planning at DIPP, therefore further on in this thesis, no specific calculations are made regarding them.

Project	**Regular costs**	**Overtime <= 2h**	**Overtime** >2h
1	€92	€114	€119
2	€100	€124	€141

Table 2: Employee costs per hour used in this thesis for the two production projects

2.3.2 The production planning tool

The current multi-project production plan is created in Excel. The plan created during and after drawing up the quotation contains the specific production activities that must be finished during a particular week. These activities are specified per row in Excel (left out of the snapshots in Figure 7 and 8). These rows also contain the estimation for the amount of labour hours that are needed. A daily production project overview was created during production project two, using days as measurement quantity. This planning can be seen in Figure 7. The different colours indicate the type of engineer. The total number of planned engineers is shown at the top of the column. A different view was used as a set-up for a future version of project 2, using the flow of the precedence relations between the production activities as guidance. The planning was also created with a weekly overview, and labour hours were used to measure quantity. The planning can be seen in Figure 8. The total number of hours needed per week is added per column and compared with the available hours. A percentage indicates how much of the initial hours are used.

There are three main reasons why the current tool is unsuitable for multi-project production planning. First, the production plan must be manually made and adapted after a disruption occurs. Secondly, a project with all its specified activities takes up a large space, and it is impossible to get a clear overview of multiple projects within one window. Thirdly, the tool does not assist in the optimization of the plan, which is why the planning might take longer than needed, or a disruption might not be optimally solved. This could also cause high fluctuations in the required labour capacity per week.

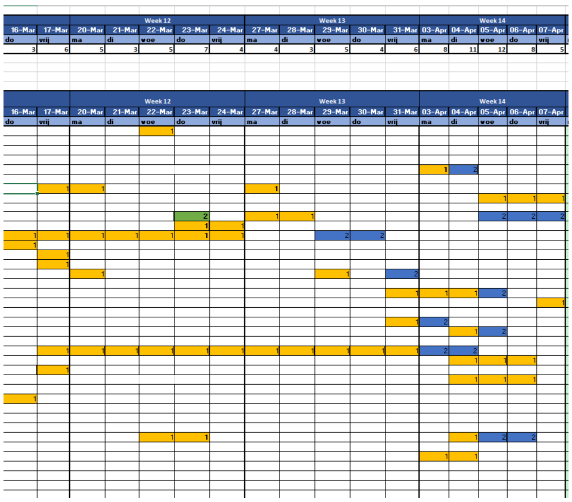


Figure 7: Snapshot of daily planning tool used for production project 2

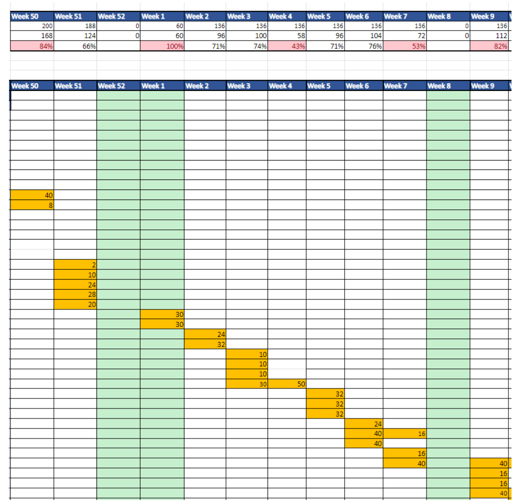


Figure 8: Snapshot of weekly planning tool for possible future use for production project 2

2.3.3 Purchasing

Purchasing must be accounted for in the general production plan since the timely arrival of parts is essential to executing the created plan. Some aspects of the purchasing process at DIPP are described here. The general purchasing department of Demcon Enschede is responsible for purchasing materials needed at DIPP. The parts that must be purchased for a product are specified in a Bill of Materials (BOM), which can also be specified to the materials required for one production activity. Before placing an order, the purchasing department asks for a quotation for each material and, therefore, gets a hold of an accurate lead time and price before the start of the project. The planning is made based on the material lead time provided by the supplier. Next to the lead time, a usual internal buffer of two weeks is applied to ensure the part has been properly processed, such as logging the material into the system, placing it in the warehouse and picking it up when the corresponding production activity is about to start.

Furthermore, parts can be classified as purchase and production parts. Purchase parts are standard parts offered by suppliers, e.g. from a catalogue. Production parts need to be made explicitly for DIPP by a supplier. The specifically made parts are more unreliable than the catalogue parts; therefore, a higher internal buffer of four weeks is applicable.

2.4 Disruptions during production

2.4.1 Type of disruptions

During production project 2, there were often a lot of changes compared to the original planning. As mentioned in the scope in Chapter 1, this research will focus on two large categories of disruptions: a change in production hours needed or a change in the material lead time of a production activity. The specifics of these categories were identified during interviews with the assembly coordinator, configuration engineer, and project manager and are described below.

1. A change in production hours needed for a production activity Since the products at DIPP have not been built before or only a few times, they are still in the process of improvement, and changes can be made to each product's design. These changes can have several causes. First, when the machine does not function the way the client wants, there could be a wish to re-design and build a section. Secondly, during testing or integration, a section cannot function as agreed upon with the client or function at all. Parts of the section, or the whole section, must be re-designed and built. Thirdly, an ordered part can be produced incorrectly, so it doesn't fit in the machine. Building the part out and the new part in can take time. Lastly, as the production times planned are estimates, the actual production times can be lower or higher, even without the above disruptions.

2. A change in the earliest start time of production of a production activity When not all parts needed for an activity are present in the planned production week, the activity must be postponed. There are several reasons why a part might not be present on time. First, the order for the Bill of Materials (BOM) of a module is passed too late from the project managers to the purchasing department. A second reason is the late placement of an order by the purchasing department at the suppliers. Both result in a time frame that is too short for product delivery. A third reason is the incompleteness of the BOM, which leads to parts not being ordered. This could, for example, be the case when the technical product files do not contain certain parts needed to integrate sections of the machine. The last and foremost reason for missing parts is the unreliability of the lead times provided by suppliers. This can be the case when purchased parts are not in stock any more at a supplier, so they have to produce or re-order them first. Another reason is that the raw materials for production parts are not available, and thus, the supplier cannot deliver the requested part.

Disruptions that fall outside these categories are not directly addressed in this thesis. These could be disruptions like employee sickness, the postponement of an entire project due to budget problems, or employee holidays.

2.4.2 Effect of disruptions

The above disruptions can result in deviation from the initially planned labour hours or start times. During the past production projects, several approaches were taken when a disruption occurred. These approaches are discussed below.

1. A change in production hours needed for a production activity When extra labour hours were needed, the first option was to look for a solution within the already available capacity, either by checking if capacity can be moved or by seeing if overtime can be embedded. This could also be done by contacting other Demcon companies regarding available employees. Extra hours could be arranged through a secondment agency if the change was visible on time. The need for more hours could result in the production exceeding the set deadline. When fewer hours are needed, the planning could be moved forward, keeping the available capacity in mind.

2. A change in the earliest start time of production of a production activity When the materials for a production activity did not turn out to be complete at the start of the planned module building, the project manager would suggest other activities that could be executed instead. This suggestion was based on the completeness of other activity materials, the available mechanics that week, and the precedence relations. When looking at material completeness, ideally, an activity with all parts present was chosen, but if not available, a threshold of 85 per cent completeness was set. However, this means that the production activity would need to be split over several sessions, as completion could only happen when all parts arrived.

2.4.3 Available data on disruptions

No precise data is available on the disruptions during the two production projects that led to changes in the plan. However, some sources can help us understand the labour hours and lead time disruptions. The purchasing department documents ordering and receiving material in Demcon's internal system. This means that for both projects, the order date, the planned arrival date, and the actual arrival date of the parts are available. Based on this, we can calculate the expected and actual lead time and the difference, indicating the range of lead time disruptions. Furthermore, the number and effect of disruptions can be classified into ranges, giving insight into the distribution of the lead time disruptions. Some edge cases have been removed for the distribution of the disruptions, either because the data for a part was incomplete or because the change was huge due to the original lead time being very small. In the latter case, the significant change would affect the distribution highly, but in practice, the delay of small parts does not affect the production planning much. Furthermore, our thesis studies production planning based on an activity's longest material lead time, making disruptions to shorter lead times even less critical. The distributions per project are visualised in Figure 9 and 10 and are presented as a multiplication factor to the original estimate. The distribution for production project one ranges from 0.6 to 1.9 of the original lead time, with most disruptions having a factor of 1.4. Notable is the large gap between the factors 0.6 and 1.4. Production project 2 shows a more even distribution of disruptions. The range lies between 0.5 and 1.8, and most disruptions have a factor of 1.2 as a delay.

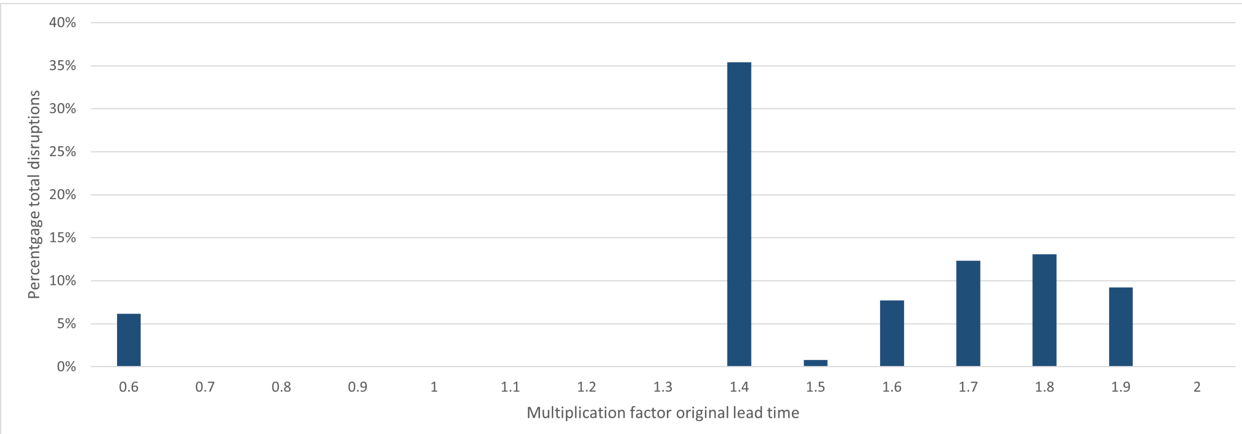


Figure 9: Percentage or total disruptions per multiplication factor of original lead time for parts in production project 1

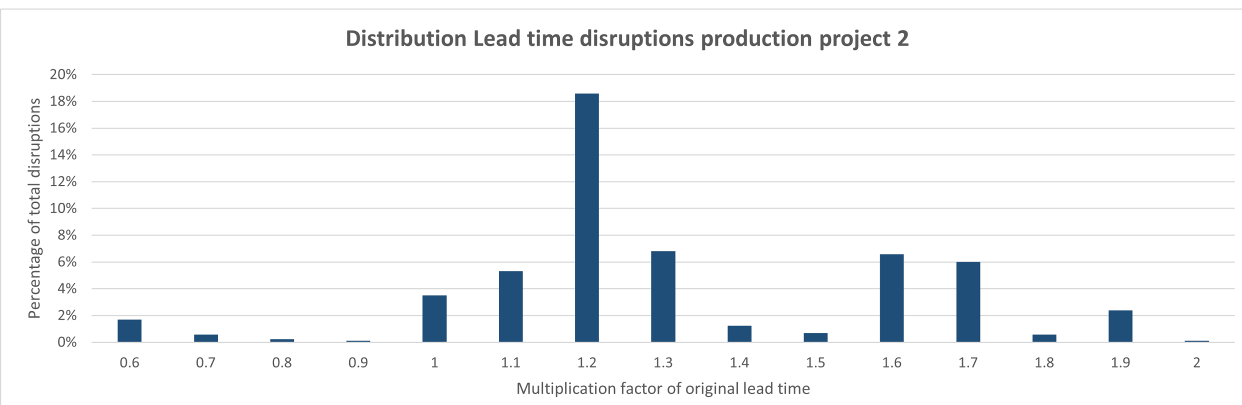


Figure 10: Percentage or total disruptions per multiplication factor of original lead time for parts in production project 2

Regarding hour disruptions, there is less data available. The documentation of production project 2 does not clearly show the difference between the planned initial hours and the total amount needed. For a few activities, the difference is documented, which all show decreased hours. This does not represent the overall distribution well, as the labour hour budget has increased by more than 40 percent during production. There is also no precise data on the total number of disruptions; however, the project manager indicated that there were disruptions every day at some point, making the total number of disruptions high. The distribution of the available data can be seen in Figure 11.

The change in hours has been documented for the currently running production project one: these changes range from a factor of 0.3 to 1.8. However, this data only contains changes in ten activities and does not show a clear distribution. Next, with the knowledge at the time of writing, the total hours needed for the project have increased by more than 20 percent. The distribution of the available data can be seen in Figure 12.

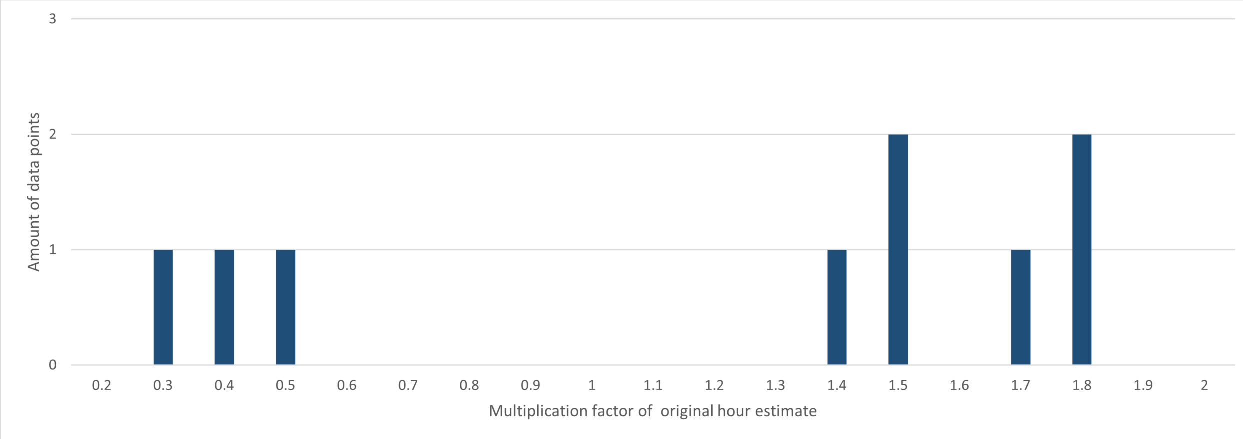


Figure 11: Data on hour disruptions as a multiplication factor of original hour estimate for activities in production project 1

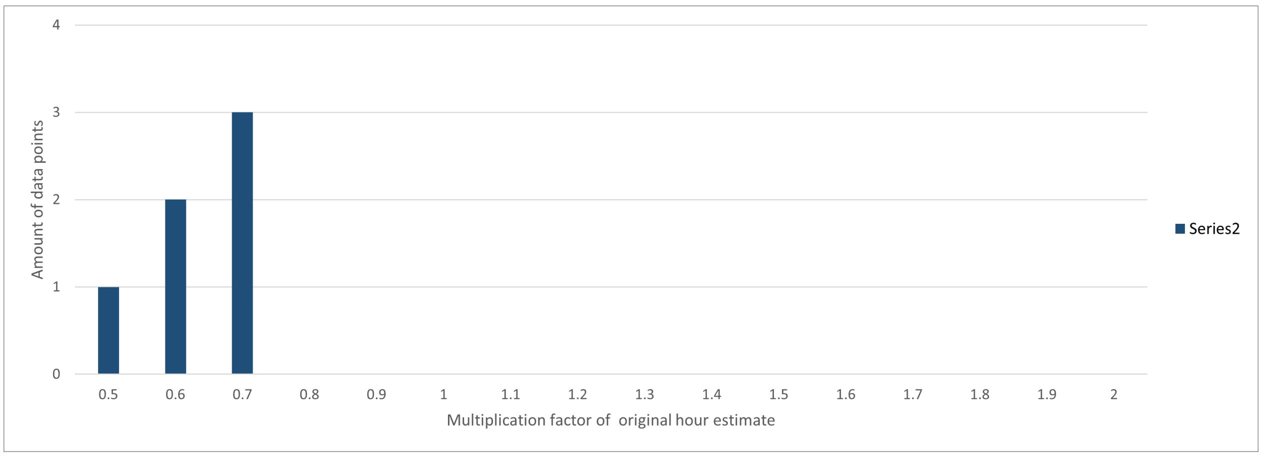


Figure 12: Data on hour disruptions as a multiplication factor of original hour estimate for activities in production project 2

In conclusion, the data on the material delays gives insight into the range and distribution of the lead time disruptions. Data on the labour hour disruptions only indicates the range and the peak of the distribution based on the total percentage of extra hours needed.

2.5 Conclusion

This chapter identifies several aspects of the current multi-project production planning method. The most important elements are summarized below for further research.

- A generalization of machines produced at DIPP is made, stating that all machines consist of several (sub-)activities with precedence concerning the production order, labour hours estimates and the longest lead time for their needed materials.
- The current project planning method is described, and the focus of the research is on two steps in the current method: The estimation of the needed hours, which can be used in the step 'Project manager makes a general plan, and a quotation is drawn up' and assisting in the updating of the initially planned hours when a disruption occurs, which relates to the step 'Planning is updated based on current status'.

- Aspects of the current project planning method that need improvement are the amount of manual work, the overview of multiple projects, and the assistance in re-planning after a disruption.
- Disruptions to the production planning are placed into two general categories: a change in production hours and a change in the start times of production of a specific module.
- Data on past disruptions is limited. Still, the distribution of delayed materials and some data on hour changes give insight into the range and distribution of lead time and hour disruptions.

3 Literature Review

This chapter provides a literature review to provide the theoretical framework for this research. The study answers the following research question:

Which methods are presented in the literature to create a robust production plan?

This chapter is divided into three parts. First, the thesis topic, creating a robust labour-hour production plan at DIPP, will be classified. This classification can then be used to find existing production planning methods and available options for creating robustness.

3.1 Classification of the Problem

This section discusses the level of the production planning problems and the type of manufacturing at DIPP. It also studies the kind of organisation.

3.1.1 Managerial level

Planning problems, of which production planning is a subsection, can be divided into three different hierarchical levels: strategic, tactical and operational. Hans proposes a hierarchical planning and control framework (Hans et al., 2007) based on the original framework of De Boer (De Boer, 1998). The framework identifies the three functional planning areas: technological planning, resource capacity planning and material coordination. Combined with the hierarchical levels, the framework provides the associated activities for each quadrant.

The production planning problem at DIPP is associated with the column resource capacity planning since the needed labour hours and resource capacity estimations do not match reality. The original estimation of the required hours to create the original planning and quotation falls within the tactical field. When production has started, optimally using the fixed capacity by rescheduling falls within the offline operational field.

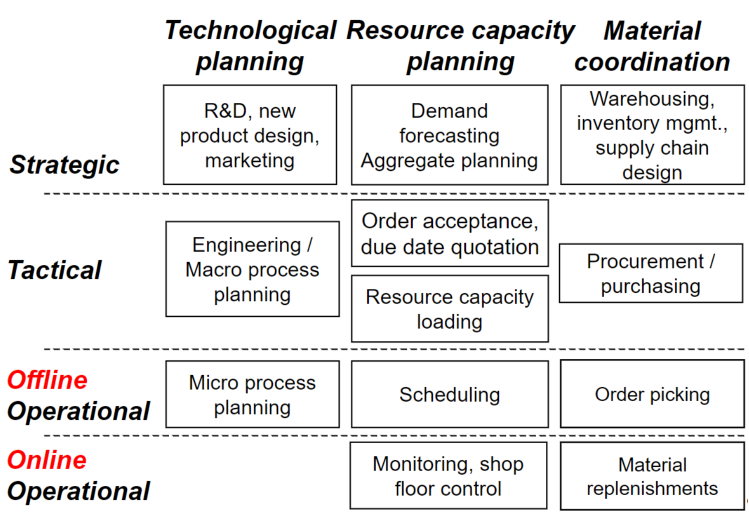


Figure 13: Hierarchical planning and control framework by (Hans et al., 2007)

3.1.2 Type of manufacturing

The Customer Order Decoupling Point (CODP) can be used to classify the manufacturing environment at DIPP. The CODP indicates the point in the material flow where a product is assigned to a specific customer (Olhager, 2010). Depending on the position of this point, the manufacturing environment can be classified as one of the four environments: make-to-stock, assemble-to-order, make-to-order, and engineer-to-order. Make-to-stock means that products are fabricated and assembled for inventory to match forecasted demand. With make-to-order, the company starts production after an order has been placed, and the product is delivered to the corresponding customer after production completion. Assemble-to-order is between MTS and MTO, has pre-fabricated items based on forecasts and assembles the product when an order arrives. The last category is engineer-to-order, where products are fully designed to the customer's wishes. (Zijm, 2000). An overview is given in Figure 14.

The production environment at DIPP is similar to that of MTO and ETO. Like MTO and ETO, production starts only after an order is placed. Although a machine's design is not done from scratch at DIPP, changes are made during and between productions. Furthermore, machine batch sizes are small, and production is difficult to standardize. Therefore, the production environment at DIPP most closely resembles that of ETO.

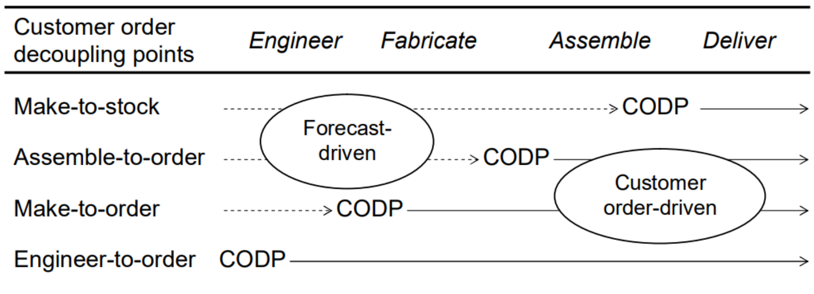


Figure 14: Different customer order decoupling points by (Olhager, 2010)

3.1.3 Multi-Project Organisations

Another framework proposed by Hans (Hans et al., 2007) positions multi-project organisations based on their dependency and variability. As DIPP might deal with multiple production projects simultaneously, this framework can also be applied to the situation at DIPP. The variability in the framework relates to information uncertainty at the tactical and/or operational stages. The dependency refers to the project's dependency on external factors, such as material coordination, subcontractors or resource sharing with other internal projects. The framework, shown in Figure 15, creates four quadrants that distinguish between 'High' and 'Low' of each factor. The Low-Low (LL) quadrant is typically seen in single-project organisations where projects are clearly specified in advance and routinely executed. The Low-High (LH) quadrant is associated with projects highly dependent on external factors, e.g., an MTO wooden furniture maker where several orders might need the machines. The High-Low (HL) quadrant has dedicated resources but a high variability, which can be the case in large construction projects dependent on the weather. The last case, High-High (HH), is mainly associated with ETO environments, where resources are shared, but the planning is also often disrupted by changing customer requests. Organisations in the HH quadrants have the most complex planning problems.

DIPP's dependence on external factors can be classified as high because of the possibility of external disruptions during production and the shared labour resources between the multiple projects at Demcon. The variability is also high, as there is uncertainty about a product's material lead times and the time needed for production. Therefore, DIPP's production planning can be classified as HH.

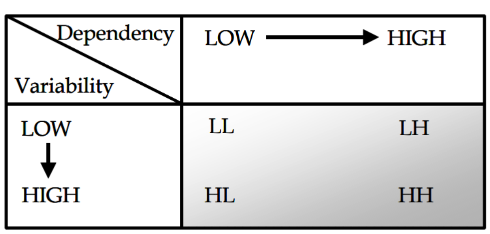


Figure 15: Positioning framework for multi-project organisations based on their dependency and variability, by (Hans et al., 2007)

3.2 Robust Production Planning

Based on the above classification, the literature study focuses on planning models at both the tactical and offline operational levels. This section focuses on selecting an appropriate model for this thesis. The Resource Constrained Project Scheduling Problem (RCPSP) and Rough-Cut Capacity Planning (RCCP) models and their variants are discussed as options. Furthermore, research into production planning robustness is conducted to deal with the ETO production at DIPP and the high variability and dependability.

3.2.1 Production planning and scheduling

Representation

During the production of a machine, certain technological constraints such as activity duration, precedence relations and capacity restrictions affect how the production can be done. A way to represent the total production restrictions is through a graph, also called activity on the node (AoN) network, first introduced by Wiest and Levy (Wiest and Levy, 1977). The different production activities are represented by nodes (N), and their precedence relations are shown by the arcs (A); the graph is therefore defined as G = (N, A). The production graph can be specified by mentioning the duration of an activity at each node or, if needed, the start-up times. An example graph of a project with five activities and their corresponding durations can be seen in Figure 16.

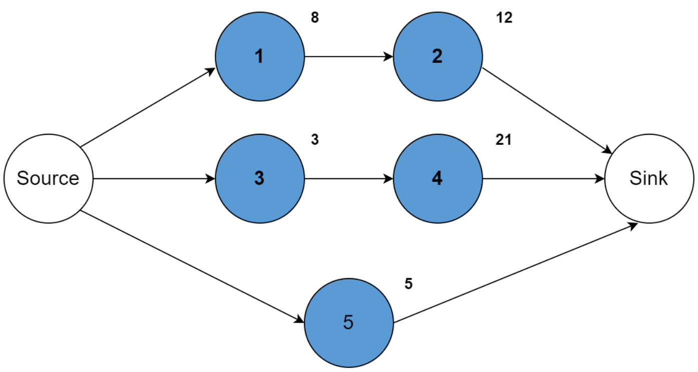


Figure 16: Production restrictions represented as a graph, the nodes and edges represent the activities and their order. The number on the top right of an activity is the total hour needed.

	1	2	3	4	5
1	-	1	-	-	-
2		-	-	-	-
3			-	1	-
4				-	-
5					-

Figure 17: Precedence relations of production activities in precedence matrix

The source and sink are dummy nodes introduced to indicate the start and finish of the project. They cost zero time and do not affect the schedule. The other nodes are numbered to their corresponding activities, and the duration of the activity in hours is specified at the top right. The graph representation can provide insight into a baseline schedule and help determine the (peak) capacity demand. The graph also gives insight into the critical sequence, which is a sequence of activities and precedence relations that determines the duration of a project (Herroelen and Leus, 2004). In Figure 16, the sequence *Source - 3 - 4 - Sink* takes 24 hours. All other sequences take less time, so this is the critical sequence, also called the critical path. In the case of a deterministic setting, the project deadline could be set at 24 hours. When there is uncertainty, however, the slightest delay in the critical sequence will delay the project; thus, the project is not robust. Project robustness is closely related to flexibility. If a project schedule is flexible, it can easily be repaired when a delay happens and changed into another good quality schedule (Herroelen and Leus, 2004). Ways to create robustness in a project schedule are discussed in Section 3.2.1.

Another way to present the precedence relations of a project is through a precedence matrix (Demeulemeester et al., 2003). The precedence matrix uses binary to indicate whether a precedence relation exists between two nodes. So if the value of a relation between an activity i and an activity j is set to 1, activity i precedes activity j. This binary approach is a good way to give the precedence relations as input for a model. An example of a matrix for the example project in Figure 16 is shown in Figure 17.

Models

There are several ways to create a production plan or schedule. This section discusses the general Project Scheduling (PS) models and the RCCP and RCPSP and selects the best fit for this thesis.

Project scheduling is a general term that refers to creating a project schedule, considering the project jobs with the restrictions of the precedence relations. The objective is to minimize the makespan while adhering to these constraints. Several variants of project scheduling deal with the uncertainty in job processing times and the necessity of certain operators. A more specific version of project scheduling that incorporates workforce constraints is the RCPSP (Pinedo, 2009). As this thesis is focused on determining the needed labour hours for a project and on the optimal use of the hours, which both fall under workforce constraints, the RCPSP will be studied. Next, Hans et al. mention, besides the RCPSP, the RCCP as a suitable method for resource capacity planning (Hans et al., 2007).

RCCP - Resource Constraint Capacity Planning The RCCP is a suitable method for medium-term capacity planning and deals with relatively large work packages (Gademann and Schutten, 2005). The RCCP is ideal for making decisions about due dates and work levels (De Boer, 1998). De Boer mentions that the planning horizon of the RCCP should be at least half a year and is usually split into weeks. The work packages are divided over the weeks and are defined as total work per resource. The paper of Gademann and Schutten distinguishes two variants of the RCCP model: the Time-drive RCCP, which may use irregular capacity to meet a hard deadline, and the Resource-driven RCCP, which may use extra time to prevent using irregular capacity. The Time-Driven RCCP focuses on minimization of extra capacity while finishing the jobs within their (hard) due dates. The model ensures completion of all jobs according to all technological constraints, e.g. precedence relations and release and due dates. The Resource-Driven RCCP is similar to the Time-Driven; however, the objective function focuses on minimizing lateness instead of extra capacity. The constraints are also changed so that a job can be completed after the given (soft) due date.

(De Boer, 1998) and (Wullink, 2005) also discuss a resource-loading model similar to the RCCP. The proposed model, called the hybrid resource loading model, can balance time and resource constraints. The objective function is shown below.

$$\min T \sum_{t=0}^{\zeta_i} \sum_{i=1}^{K} O_{it} + \sum_{j=1}^{n} \sum_{b=1}^{n_j} \theta_{bj} \partial_{bj} \tag{1}$$

In the objective function (1) the irregular capacity O_{it} and tardiness ∂_{bj} are minimized over the entire planning horizon T.

RCPSP - Resource Constraint Project Scheduling Problem The RCPSP focuses on allocating resources over time to tasks or activities. Important constraints are often limited resource capacity and technological constraints. The standard RCPSP designs a schedule σ by specifying a completion time $C_j(\sigma)$ for each project activity. Each project consist of N activities A_1, A_2, ..., A_N, and there are K resources. Each resource R_k has a constant availability of Q_k units. The precedence relations are defined in the set P_j, which specifies the direct predecessors of activity j. The objective is to find a feasible schedule where the total makespan is minimized as shown in equation (2), and the deadline is met (De Boer, 1998).

$$\min C_{max}(\sigma) = \max_{j=1,\ldots,N} C_j(\sigma) \tag{2}$$

The schedule is found feasible if all resource and capacity constraints are met, shown in equations (3) to (5). Constraint (3) indicates that all planned capacity should stay within the boundaries of the resources planned at time t. Which is defined in the constraint below. In constraint (5) the precedence relations are met such that the predecessors of an activity are finished before the completion of that activity.

$$\sum_{A_j \in \chi_t(\sigma)} q_{jt} \leq Q_k \quad \forall k \in K \tag{3}$$

$$\chi_t(\sigma) = Aj | Cj(\sigma) - pj \leq t \leq Cj(\sigma). \tag{4}$$

$$C_h(\sigma) \leq C_j(\sigma) - p_j \quad A_h \in P_j, j \in N \tag{5}$$

Both the RCCP and RCPSP incorporate resource-related constraints. The RCCP uses irregular capacity, tardiness, or a combination of both to determine a schedule, and the RCPSP plans within the set boundaries of the resource and deadline constraints. The situation at DIPP allows flexible determination of resource levels but does not plan for irregular capacity or tardiness, which does not precisely fit the RCCP or RCPSP. Next, the production plan must be optimized regarding the specific precedence and duration constraints between the activities represented in both models. The RCCP, however, focuses on large work packages, while the RCPSP focuses on smaller activities and their optimal order. The products created at DIPP are divided into specific activities, each with activity duration estimates, which is why the RCPSP seems the best fit. Furthermore, when drawing up a quotation, the deadline has already been set in consultation with the client. This is a boundary for the resources, which is only incorporated in the RCCP in combination with the consideration of overtime. In the RCPSP, the deadline boundary can be integrated without the use of overtime. The RCPSP seems to best fit the production planning needs of DIPP. Further study on how to adapt the RCPSP to the specific needs of DIPP is discussed in the next section.

Optimization

The standard RCPSP optimizes the minimization of the maximal schedule, also called the makespan. Several other objectives can also optimize the project schedule created by the RCPSP. A recent survey gives an overview of the objectives in the RCPSP (Hartmann and Briskorn, 2022). The overview is summarized in Table 3.

Type	**Focus**	**Objective focus**
Time-Based	Finishing in a certain time frame	Make span, tardiness, processing time
Robustness-based	Activities that take longer or cost more than expected	Slack times, expected costs under worst-case estimations
Rescheduling-based	Current schedule is infeasible/not optimal	(Weighted) deviations of the start or finish times of previous schedule
Resource-based	Cost of resources	Total resource costs
Resource renting-based	Cost of renting resources	Total resource renting costs
Resource levelling-based	Creation of smooth resource profile	(Weighted) squared capacities or changes in capacity between time periods
Cost-based	Project costs	Total project costs
NPV-based	Cash flow of projects	NPV of project

Table 3: Types of optimization for RCPSP

RCPSP models can have multiple objectives, which can be the case when each objective is assigned a specific weight or the objectives are optimized in a certain order. Several objectives are relevant to the situation at DIPP. First, a time-based objective is necessary to ensure a timely finish of the project and limit the project's duration. An option for such an objective is already shown in equation (2) by minimizing the maximum makespan. Secondly, the capacity needed for a project must be estimated and should not vary too much from week to week so that a fixed team can work on the project. Especially when there are no labour resource boundaries for the original planning, thus removal from constraint (3). Therefore, the resource-levelling objective is important. A common resource levelling objective is shown in equation (6); the objective minimizes the weighted squared capacities. The c_k represents the costs of a resource k , R_{kt} represents amount of resource k planned in time period t. Another possible objective focuses on the changes in levels between periods and minimizes the differences between the sequential periods as seen in equation (7). Thirdly, the robustness-based objective might be relevant since the activities at DIPP have an uncertain duration and can take longer because of the several disruptions mentioned in Chapter 2. However, clear considerations between robustness levels are needed to put robustness in the objective. These are not currently known at DIPP because of a lack of disruption data. Therefore, other ways to include robustness in the planning are discussed in 3.2.1. In conclusion, the objectives related to the makespan and resource levelling are most appropriate for creating the production plan for DIPP.

$$\min \sum_k c_k \sum_t R_{kt}^2 \tag{6}$$

$$\min \sum_k c_k \sum_t (R_{k,t+1} - R_{kt})^2 \tag{7}$$

A rescheduling-based objective could also be relevant for adapting the initial plan when a disruption occurs. Working is impractical when many changes are made to the plan. Therefore, a factor that measures the deviation from the initial plan is further discussed at 3.3.

Proactive robustness in production planning

Robustness in a project can be obtained via proactive (also known as predictive) and/or reactive approaches (Aytug et al., 2005). The proactive approach tries to deal with possible uncertainties before the start of a project by, for example, incorporating slack into the planning. The reactive approach aims to deal as best as possible with disruptions when they happen. These disruptions might be solvable within the proactively arranged slack or need a more complex solution (Wullink, 2005). This section will discuss proactive approaches; in Section 3.3, reactive approaches are discussed.

Robustness in a model can be created by incorporating slack. Slack is traditionally seen as a buffer of a resource. Fireman et al. extend this definition by defining three different usages of slack in production planning. The first is redundancy, thus arranging additional resources above the minimum necessary to perform a function. The second is work-in-progress, where extra jobs are ready to be processed between other process steps to keep a stable work-in-process. The last category is margins of manoeuvre, which is the creation or maintenance of margins to ensure that the system can function when unexpected demand arrives (Fireman et al., 2023). Concerning the labour hour need uncertainty at DIPP, the needed slack would fall in the first category by planning more time or people than the minimum required. Next, considering the dependability on the timely arrival of parts, extra margins regarding the project's start time could be used to prevent postponing production until a part has arrived.

Studying examples from the literature, authors have incorporated robustness in their models in various ways. The first way is to maximize robustness in the objective. This can be done using a scenario-based approach, as demonstrated by Artigues. The objective focuses on minimising absolute regret, which is the difference between a makespan of a scenario and the optimal makespan (Artigues et al., 2013). Zang also introduces robustness in the objective using the Risk of Activity (RAD) delay. The RAD looks at risks in terms of costs when an activity is delayed. The paper introduces an algorithm to add time buffers in the model to reduce the RAD (Zhang et al., 2020).

Abbasi and Al Fawzan introduce bi-objective models where robustness is maximised next to the makespan minimisation. Abbasi maximized the amount of floating time in a model (Abbasi et al., 2006), and Al Fawzan maximizes the sum of free slack in the model.

Another common approach is using a robustness parameter that can be adapted to adjust the robustness of the schedule. So does Balouka introduce a parameter that indicates the number of activities that can deviate from the most pessimistic duration (Balouka and Cohen, 2021), and does Li introduce a parameter that adjusts the duration per activity (Li et al., 2015). Furthermore, Fu introduces a level of allowable risk that is taken into account to compute the minimum robust makespan.

Lastly, Moradi introduces a model that uses critical chain project management (CCPM) to determine where to insert buffers into the schedule. Several rules are introduced, such as extra buffer when a chain merged with the critical chain and buffer insertion when the capacity needed changes (Moradi and Shadrokh, 2019).

Looking at the situation at DIPP, there is a lot of uncertainty regarding the duration and start time of activities. Therefore, using slack in extra time and labour resources is a good possibility. While a robustness-based objective offers specific considerations regarding what amount of slack to apply, there is too little data at DIPP regarding production scenarios. Therefore, the most suitable approach is using robustness parameters that indicate the needed amount of slack. Ways to incorporate slack are discussed in the next section.

3.2.2 Incorporation of slack

(Fireman et al., 2023) discusses the placement of slack resources and their benefits. The placement can determine whether a slack is a potential waste, effective, or even actual waste. As discussed before, there is little data on the disruptions at DIPP and, therefore, on the needed placement of slack. The slack could be placed based on a robustness parameter as mentioned by (Li et al., 2015). A more refined option could also be through sample average approximation (SAA). (Kim et al., 2015) describes a guide to the SAA approach. The SAA takes a sample from a function or distribution and creates a deterministic function based on a chosen sample. This deterministic function can be optimized, assuming the samples are independent and identically distributed. While sample approximation is hard based on the available disruptions data, a simpler approach could provide insight into the proactive placement of slack. By taking the average demand for slack over randomly generated scenarios, the required slack for a certain scenario could be generated. The slack placement could then be fixed for deterministic solving against other disruptions. A last option for slack placement could be at the end of a project, discussed by (Martens and Vanhoucke, 2017). The paper discusses the purpose of the different amounts of slack and its ability to resolve project uncertainties at the end of projects.

3.2.3 Literature comparison production planning

A literature table was created to compare the literature related to the situation at DIPP. This table can be used to identify suitable model aspects and find a literature gap that this thesis can fill. The table is shown in Table 4.

Based on the above sections, the model for DIPP will be based on the RCPSP. Next, the objective should include the makespan and resource levelling. Besides, the model should incorporate robustness to reduce uncertainty in the needed labour hours for activities and material lead times. Using this knowledge, the literature research was specified to find models closely related to the potential model for DIPP.

The table highlights several combinations of objectives. The makespan is minimized in eight models, and resource levelling is used in three models. The combination occurs three times in (Ghoddousi et al., 2013), (Shahsavar et al., 2015) and (Zhang and Zhong, 2018).

Furthermore, robustness or uncertainty is incorporated in eight different models. Multiple models do use it in the objective by, e.g. maximizing the floating time in the model (Abbasi et al., 2006) or by optimizing the maximum absolute regret over multiple scenarios (Al-Fawzan and Haouari, 2005).

Besides being directly related to the objective, robustness is obtained in multiple ways. (Fu et al., 2015) use a robustness parameter that determines the duration of the activities. By considering this parameter, the objective, makespan minimization, is optimized. (Balouka and Cohen, 2021) and (Li et al., 2023) also incorporate the robustness of activities indirectly, but they define the activity duration more extensively. Balouka and Cohan use an uncertainty set, which determines the duration, and Li et al. estimate the duration's range and most likely values. These approaches give more reliable results but need more data than just using a robustness parameter.

The paper of (Zhang and Zhong, 2018) shows the most similarity with the approach taken by this thesis. Zang minimizes the project makespan, maximizes stability and maximizes resource levelling. Furthermore, the paper incorporates uncertainties using a stochastic duration distribution of the activity durations and a robustness parameter for resource breakdowns and failures. In contrast to the approach by Zang and Zong, this thesis will also include material lead time uncertainty and use slack to create robustness against it. Furthermore, the paper of Zang and Zong focuses on the activities of one project, while this thesis will incorporate uncertainty with a combination of projects. To the best of our knowledge, the literature has not previously taken this approach with similar RCPSP variants.

Research paper	Model is based on	Objectives	Incorporation of uncertainty
(Abbasi et al., 2006)	RCPSP	Minimize make span, Maximize the floating time (robustness)	No uncertainty
(Al-Fawzan and Haouari, 2005)	RCPSP	Minimize make span, Maximize total sum of free slack	Rework incorporated
(Artigues et al., 2013)	RCPSP	Minimize the maximum absolute regret	Different scenarios for activity duration
(Balouka and Cohen, 2021)	RCPSP	Minimize worst-case project duration	Activity durations defined over polyhedral uncertainty set, Robustness parameter to determine activity duration
(Fu et al., 2015)	RCPSP	Minimize (robust) makespan	Starting times of activity modelled as random variable, Robustness parameter to determine activity duration, Resource breakdowns incorporated
(Ghasemi et al., 2023)	RCPSP	Minimize make span, Maximize quality, Minimize costs	Rework incorporated
(Ghoddousi et al., 2013)	RCPSP, DTCTP [1]	Minimize project duration, Minimize variability in resource usage histogram, Minimize total project costs	No uncertainty
(Jiang et al., 2019)	RCPSP	Minimize completion time all projects	No uncertainty
(Li et al., 2015)	DTCTP	Minimize make span	Estimate range and most likely values of activity durations, Cost intervals
(Shahsavar et al., 2015)	PS	Minimize make span, Minimize variability in resource usage, Minimization of total resource costs	Activity duration scenarios created
(Vasilyev et al., 2023)	RCPSP	Minimize the total sum of maximal daily workload, Minimize total schedule costs	No uncertainty
(Zhang and Zhong, 2018)	RCPSP	Minimize project makespan, Maximize stability, Maximize resource levelling	Using stochastic duration distribution to determine activity duration, Robustness parameter for resource breakdowns and failure distributions
This thesis	RCPSP	Minimize project makespan, subject to robustness parameter, Minimize variability in resource levels.	Robustness parameter (indicating slack) for activity duration and material lead times.

Table 4: Literature table comparing literature that shows similarities to the approach taken by this thesis

[1] Discrete time-cost trade-off problem

3.3 Reactive re-scheduling within a plan after a disruption

The above-discussed approach assists the project manager with creating a proactive, robust plan for production. However, at the moment of a disruption, the way that is reacted, thus how the plan is changed, also affects the total labour hours used. To determine how to best respond to the disruption, a reactive model that re-optimizes the sequence of the activities within the set boundaries of the proactive model can be used. When looking at the literature, the distinction between reactive re-planning and reactive re-scheduling is made by the timing that the reaction is made. Re-planning is often on a broader scope and can happen before the production has started, as the schedule is usually made weeks or months in advance. Re-scheduling occurs during production, and there is often limited time to find a new solution. Re-scheduling focuses on minimizing the impact of the change. It can also incorporate the option to fixate activities that, for example, have already happened or cannot change. The schedule is then re-optimized outside these activities (M. Calhoun et al., 2002). The re-scheduling approach is more suitable since disruptions to the production planning at DIPP can occur during production. The created re-scheduling model should be able to deal with the two types of disruptions defined in Chapter 2: changing activity durations and changing start times of activities when e.g. materials arrive earlier or later. These can be put in the general categories of resource-based and job-based disruptions (Mård, 2021).

Three things are essential to deal with these disruptions: how much of the plan will be rescheduled, when the rescheduling will be done and according to what policy the schedule will be changed. For the first category, the options are to generate a completely new schedule, which consists of fully re-sequencing the not yet executed part of the project, or only to make minor adjustments to repair the disruption, which is usually done using the simple right-shift-rule (Elloumi et al., 2017). Three policies regarding the timing of rescheduling have been mentioned in the literature. These are periodic, event-driven and hybrid policies. Periodic rescheduling generates new schedules at consistent intervals. Event-driven rescheduling is triggered at the moment the event occurs. Hybrid rescheduling reschedules at periodic intervals but also occasionally at the occurrence of the event (Ouelhadj and Petrovic, 2009).

Ouelhadj and Petrovic specify four scheduling policies that are classified based on the chosen proactive and/or reactive approach (Ouelhadj and Petrovic, 2009).

- Completely reactive scheduling: this method only generates schedules in real-time and uses priority rules to select the next job.
- Predictive-reactive scheduling: the already created schedules are revised when an event occurs. Most are based on simple scheduling strategies, which can lead to large schedule changes.
- Robust-predictive-reactive scheduling: the same as predictive-reactive scheduling, but the effect of the disruption is minimized in the schedule. Here, usually, both the makespan of the new schedule and deviation from the original schedule are used in the objective function.
- Robust proactive scheduling: to predict disruptions and account for them in the schedule. The objective is to minimize the maximum lateness, so the disruption is often compensated by inserting additional time into the schedule.

The situation at DIPP requires a robust proactive and reactive approach. The robust proactive approach ensures room to deal with the unknown disruptions in the original plan. The reactive approach is to re-optimize the planning by rescheduling since the amount and timing of the disruptions are hard to predict. Reactive rescheduling models use several possible objectives of which the minimization of the makespan and maximization of stability are common (Chakrabortty et al., 2021) (Elloumi et al., 2017) (M. Calhoun et al., 2002). Stability can be maximised by measuring the differences between original and newly generated plans. The way that re-scheduling happens in models differs. So did Calhoun introduce a tabu-search for activity re-scheduling (TSAR) that minimizes the number of activities that are changed, and did Charkrabortty introduce the Event Based Reactive Approach (EBRA), which should be used immediately after a disruption. EBRA looks at the differences between the baseline and realized schedule and re-schedules under sets of already completed activities (fixed), incomplete activities (should be first), and future activities. Furthermore, the maximum resource usage is also taken into account. A recent literature review of proactive and reactive scheduling also highlights the option of a match-up point. This means that the rescheduling is done so that the plan is the same as in the initial plan after a specific time interval. The interval is defined from the occurrence of the disruption to a set match-up point in the future(Erlenbusch and Stricker, 2024).

Looking at the situation at DIPP, the common objectives of makespan minimization and maximization of stability fit a rescheduling model. Next, the resources planned by the proactive model determine the boundaries for rescheduling. Furthermore, the option to freeze already finished activities is needed to deal with schedule changes during production. A match-up point is unnecessary as stability maximisation is already part of the objective.

3.4 Conclusion

The literature study in this chapter provides insight into the type of problem DIPP faces, which approaches can be taken, and what this thesis's contribution is to the literature. The main points of this chapter are summarized below.

- The estimation of the needed labour hours at DIPP has been classified as a tactical-level problem, and the optimal use of the planned hours during production by re-scheduling has been classified as an offline-operational level problem. Engineer-to-order closely resembles the manufacturing environment at DIPP. Regarding DIPP as a multi-project organisation, the variability and dependability of the situation at DIPP are seen as high.
- To represent the precedence relations between production activities in the model, a precedence matrix can be used as model input.
- For the situation at DIPP, a combination of a proactive and reactive approach is most suitable for the high uncertainty in the activity duration and start times.
- The pro-active model should create a plan that minimizes the production's makespan and ensures that the planned labour resources are levelled. The model can be designed by adapting the constraints and objectives of the RCPSP. Since there is no data at DIPP regarding the possible extreme values of the specific activity disruptions, the model will use two robustness parameters to indicate the extra slack that needs to be incorporated into the initial plan. The robustness parameters' values will affect the activity's duration and start time.
- For the placement of slack, three policies are discussed that could affect how useful the slack is against disruptions. The first is by equal placement throughout a project, the second is through proactive average approximation, and the third is by placing slack at the end of a project plan.
- The reactive model extends the proactive model by re-scheduling within the determined boundaries of labour resources and the set deadline. The reactive model will extend the objective of the RCPSP by minimizing the disruptions to the schedule and by introducing a set of fixed activities, which include activities that are already completed so that re-scheduling only happens from a certain point in the planning forward.
- The literature table in this chapter, Table 4 indicates that the combination of objectives and robustness parameters needed for the situation at DIPP is unique. The most significant contribution is the addition of a robustness parameter regarding the start times of the activities, e.g. material lead times, in combination with an RCPSP model. To the best of my knowledge, this specific combination is new compared to other literature.

4 Production Planning Model

This chapter describes the modelling approach taken by this research. First, the purpose of the model is specified, and the assumptions made are stated. Next, the proactive production planning model and the reactive rescheduling model are presented. The chapter finishes with the programming approach that will be taken. This chapter answers the following research question:

How should the robust production planning model be designed?

4.1 Model Design

The model outline describes the model's goal, input, and output. It is used as a guideline for further model building.

Goal
Proactive production planning model The proactive production planning model should assist the project manager with the creation of a production plan based on the given production project data, therefore focusing on the step 'general planning and quotation are drawn up', defined in the project planning approach in Chapter 2. Based on the data on the to-be-planned projects, a feasible plan should be created to indicate the needed labour hours and the weekly planning for the quotation. The model ensures that the created planning follows the precedence relations and uses the right amount of hours and lead times. Furthermore, the model incorporates lead time or labour hour slack by taking two corresponding robustness parameters as input. The model automatically calculates the new hour and lead time estimates that should be used in the planning.

Reactive re-scheduling model The re-active re-scheduling model should assist the project manager in adapting the production plan optimally when a disruption occurs that affects it, therefore focusing on the step that updates the planning during production, from the project planning approach in Chapter 2. The manager should be assisted in dealing with two types of disruptions: a change to the labour hour estimate or the material lead time of production activity. The re-scheduling model considers the disruption and optimally incorporates the changes into the plan while minimising deviation from the initial planning and using overtime. To ensure that the re-scheduling model can also be used when a disruption occurs during production, it should provide an option to select the week from which the plan can be rescheduled.

Design
First, the design of the proactive model is described, and then the adaptations needed for the reactive model are mentioned.

Proactive production planning model To make the model usable for multiple production projects, the generalization of a product made in Chapter 2 will be used. This states that all products are divided into multiple production activities, which must be built according to certain precedence relations. Each activity also has an estimation of the needed labour hours to complete it and an estimation of the needed material lead times in weeks, which is used to indicate the week in which the production of a certain activity can start. As input to the model, this information on the products, the start date, and the production deadline is given. Next, the model will use the values of two robustness parameters;

1. Robustness Hours - A parameter that indicates the robustness of the labour hour estimates of the production activities. The parameter indicates a factor by which the initial estimate is multiplied. When the parameter is above one, extra hours will be planned. The parameter can be used to incorporate slack into the planned hours of the production project. If more hours are planned than originally estimated, these extra hours can be used to deal with unforeseen disturbances.

2. Robustness Lead time - A parameter that indicates the robustness of the material lead time estimates of the production activities. The parameter indicates a factor by which the initial estimate is multiplied. When the parameter is above one, the start of an activity will be postponed by the created extra lead time. The parameter can incorporate slack into the estimated planned material lead time. If the production planning incorporates more lead time weeks, the additional weeks ensure that if a material is delayed, it might still be on time before the production starts.

The model then generates a production plan with the different production projects subject to the two robustness parameters and indicates per week the needed labour hours and the fractions of activities that need to be completed within these hours. While creating the planning, the model optimizes on the minimization of the makespan and the minimization of labour hour level variation between the weeks, both based on objective (2) and (7) from the literature review. This way, the produced planning can be used to assemble a fixed team to work on a production project for a certain period.

The model also considers multiple constraints, which can be divided into groups. A first group of constraints ensures that the production activities for each machine are completed. The model plans activities by assigning a fraction of an activity to a week. If an activity is completely planned in one week, its fraction is one. By assuring that all the planned fractions of an activity over the weeks add up to one, the completion of the activity is guaranteed. Next, a constraint is needed to calculate the required labour hours in a week, and the result can be used to determine the variation in planned labour hours between the weeks. The total variation is then used to minimize in the objective. Next, the number of weeks in which hour variation occurs is counted to ensure that the model limits the variations. The next group of needed constraints is related to the correct following of the precedence relations. As the planned start times and end times of the activities are not fixed, these must be dynamically determined in the model to ensure the correct production order. To do this, the constraints check what the first and last week is that a fraction of an activity occurs. Using these weeks, the model can ensure that activities do not start before their predecessors are finished. The model also incorporates constraints to determine the makespan of a project. The makespan is minimized per project and takes the first and last week, during which an activity for that project is planned. A last model constraint takes the material lead times of the different activities into account and ensures that from the project start date, taken as order date, the needed lead time is taken into account before the corresponding activity can start.

Re-active re-scheduling model To adapt the production planning model to the re-scheduling model, some changes are made to the objective, input and constraints. First, the model input is extended with parameters determined by the proactive plan. These include the planned fractions per activity per week, the planned labour hours per week and the fixated order times that correspond to the planning, with the chosen robustness incorporated. Next, a set of frozen weeks is introduced to ensure that the rescheduling can only happen from a specific week in the plan forward if needed. Regarding the constraints and objective, the model's focus is extended by offering the option to deviate from the planned hours to complete a production project on time. This could be by using overtime or by using fewer hours than planned. Both deviations are minimized in the objective. Next, the changes made to the initial plan by rescheduling are minimized by calculating the difference between the originally planned activity fractions and the newly planned fractions. A new constraint and objective is also added to limit the makespan of activities. This is needed as the model might spread an activity over multiple weeks to stay within the original plan. In which case, the employees at DIPP need to switch a lot between the production activities, which is impractical. The model minimizes the activity makespan by calculating the number of weeks between the start and end week of the activity. All other constraints stay the same.

Input

First, the input of the proactive model is discussed. Then, the additions for the reactive model are mentioned.

Pro-active production planning model The input of the model contains the details of the production projects that need to be planned. These include the project's name, the start date, the date from which materials can be ordered, and the deadline. Next, each project specifies the activities part of its production process and gives an estimate of labour hours per activity to ensure completion. Each activity also has a corresponding lead time that contains the longest material lead time of an item needed for that activity. Within this lead time, the material type has also been considered, as different types of material have different internal processing durations in Demcon. Furthermore, the order in which the activities must be completed is given as input as a precedence matrix. Lastly, the values for both robustness parameters are provided as input.

Re-active re-scheduling model Next to the above input regarding the production projects, the output from the proactive model is used as input to the reactive model. Therefore, the weeks in which production occurs, the amount of labour hours planned per week, and the fractions of activities per week are given as input. The robustness parameters are no longer needed as the planning has already been created with the chosen robustness. As the need for re-scheduling occurs at a disruption, input from the disruption is given. This includes the week in which the disruption occurs, the type of disruption, the activity it affects and the effect of the disruption. The week of the disruption is needed to create a set of fixed weeks so that the re-scheduling can only be done after this week. The type of disruption, in combination with the affected activity, indicates which original parameter needs to be changed. This could be the labour hour estimate or the material lead time estimate. Lastly, the effect of the disruption is necessary to update the original estimates to their new value.

Output
The outputs of the models both contain a weekly-based plan for all projects given as input on their corresponding time frame. The planning specifies the weekly labour hours needed and the fractions of activities to be completed. For the rescheduling model, the output also indicates the deviation in labour hours from the original planning.

4.2 Assumptions and simplifications

Some assumptions and simplifications have been made to create the designed model, ensuring a reasonable run time and a compact model.

General assumptions

- The production project given as input to the model can only concern the building of one machine. If multiple machines are to be built simultaneously, these must be presented as separate projects in the model.
- The generalization of a product made in Chapter 2 is considered valid for the current models, and it is assumed that future projects will also fit within this framework. The generalization states that all products are divided into (sub-)activities that must be built according to precedence relations. Each has a labour hour estimation and material lead-time estimation.
- The activity durations are independent of each other.
- There are always enough employees available for the completion of productions.
- Activities whose order is defined by a precedence relation can start in the same week as their predecessor is finishing. This is allowed since the model works on a weekly basis, but the production of an activity can take less than a week. Therefore, successors of such an activity should also be able to start in the same week.
- The activities that must be executed in a project can be split between multiple weeks. This is allowed since it does not affect the result of the production and since some activities are very long and they do, therefore, take more time than a week.
- It is assumed that the ordering of materials can start from the provided start time of a project.
- The provided deadline of the production project is fixed, meaning that the model will always produce a plan that ensures the project finishes on time, if feasible, instead of postponing the deadline. The deadline can, however, be manually put further in the future to experiment with different plans.
- The production projects that need to be in the schedule are known on time enough to create a feasible schedule within the specified boundaries of the project.

Proactive model assumptions

- *[No specific assumptions]*

Reactive model assumptions

- The re-scheduling model deals with the two types of disruptions defined in Chapter 2. These are a change in the estimated labour hours per production activity, e.g. when a design change is needed, or a change in the earliest start time of a module, e.g. when a material is delayed. Other types of disruptions are out of scope.
- When re-scheduling calls for more labour hours in a week than originally planned, the hours are updated to this higher amount. If the number of hours per week turns out lower, the amount is not updated but kept the same as the higher amount, as it is assumed employees for these hours are arranged and thus need to be paid.

4.3 Formulation proactive production planning model

The created proactive production planning model is specified below. The model aims to minimize the makespan and resource level variations, subject to the created robustness in labour hours and material lead times. First, the sets, parameters, and variables are given, and then the constraints and objective's purpose and function are given.

Sets Three sets have been defined: the number of projects that need to be planned, the range of weeks over which the projects should be planned (the range is determined by the earliest project release week and the latest project deadline) and lastly, the activities of the projects that need to be planned in. The activities of all projects are combined into one set since most constraints apply to all activities. The specific activities per project can be retrieved from the set using the correct indexes. These are calculated in advance and passed as parameters to the model.

P	Set of projects $\{1, \dots, \text{num\_projects}\}$
T	Set of weeks $\{\text{startweek}, \dots, \text{endweek}\}$
A	Set of activities $\{1, \dots, \text{total\_activities}\}$

Parameters The below parameters are given as input to the model. They provide information on the required labour hours per activity, the material lead time per activity, the precedence matrix that contains the needed order between the activities and the release dates and deadlines of the specific projects. A start and end indexes list is also introduced to get the project-specific activities from the Set A. The incorporated robustness, created through slack, is also passed through RobHours and RobLeadtime; their value indicates the factor of the labour hours or material lead times planned.

RobHours	Used to indicate the slack factor on labour hours
RobLeadtime	Used to indicate the slack factor on material lead times
H_i	Estimated labour hour required for each activity, $i \in A$
L_i	Longest material lead time for each activity, $i \in A$
ProcessTimePart_i	A fixed buffer of time DIPP sets to receive and process material.
precedence_{ij}	Precedence relation indicated between i and j, $i, j \in A$
release_p	Release time for each project, $p \in P$
deadline_p	Deadline for each project, $p \in P$
start_index_p	Start index of activities of project p in Set A, $p \in P$
end_index_p	End index of activities of project p in Set A, $p \in P$
w_m, w_h, w_{hc}	Weight in the objective of makespan (m), hour variation (h) and hour variation count (hc)
M	300000 (used as large number in constraints)
Hours_{total}	Sum of H_i, used in normalization
Leadtime_{min}	Minimum of L_i, used in normalization
Leadtime_{max}	Maximum of L_i, used in normalization
Deadline_{min}	Minimum of *deadline*, used in normalization
Deadline_{max}	Maximum of *deadline*, used in normalization

Auxiliary decision variables The below variables are determined by the model and used for the optimal calculation of the decision variable. The variables determine the weeks the activities occur, the needed weekly hours, and their variation. The makespan and required order times are also determined.

weekhours_t	Total labour hours needed in week t, $t \in T$
$\text{hourvariationweek}_t$	Hour variation between week t and the next week $t+1$, $t \in T$
totalhourvariation	Total hour variation across all weeks
$\text{hourvariationcount}_t$	Binary variable indicating if there is variation between week t and the week $t+1$, $t \in T$
summakespan	Sum of all project makespans
ordertime_i	Week in which the material with the longest lead time of activity i is ordered, $i \in A$
$\text{bin}_{t,i}$	Binary variable to help determine the first and last week of an activity, $t \in T, i \in A$
$\text{first\_bin}_{t,i}$	Binary variable to determine the first week of an activity, $t \in T, i \in A$
firstweek_i	The first week of activity i, $i \in A$
lastweek_i	The last week of activity i, $i \in A$
$\text{lastprojweek\_ind}_p$	The last week of project p, $p \in P$
$\text{firstprojweek\_ind}_p$	The first week of project p, $p \in P$
minfirstweek	The first week over all projects, used in normalization
maxlastweek	The last week over all projects, used in normalization
$\text{hourvariationcount}_{norm}$	Normalization of hour variation count to use in the objective
makespan_{norm}	Normalization of makespan to use in the objective
$\text{hourvariation}_{norm}$	Normalization of hour variation to use in the objective

Decision variable The primary decision variable contains the decision on the amount of work planned per activity per week. This amount is a fraction of the total work that needs to be done for an activity. The model should determine the placement of the fractions over the weeks while minimizing the objective.

$\text{x}_{t,i}$	Variable indicating the fraction of activity i scheduled in week t, $\quad \text{t} \in T, i \in A$

Constraints The constraints below are divided into several sections. The purpose of the constraints is explained in each section.

Ensure the completion of the activities Constraints (8), (9) ensure that each activity is planned completely and thus that each production project will be completed. Therefore, all the fractions over the weeks should add up to exactly one.

$$\sum_{t \in T} x_{t,i} \geq 1, \quad \forall i \in A \tag{8}$$

$$\sum_{t \in T} x_{t,i} \leq 1, \quad \forall i \in A \tag{9}$$

Calculate the needed labour hours per week and the difference in hours between the weeks The equations below ensure that all the labour hours for the activities are planned. Constraint (10) uses the determined fractions and multiplies them by the hours needed to complete an activity. The hours are also multiplied by the set robustness factor for labour hours to ensure that the determined slack over the hours is incorporated in the final week hours. Furthermore, the goal of a stable workload is met, such that a set team of employees can work on the production of the machine. Constraints (11), (12), calculate the difference in planned week hours between two consecutive weeks. The two constraints are needed to incorporate a negative hour difference. The restrictions of the constraint ensure that it does not hold for the last week since there is no variation to calculate for the week after. Constraint (13) adds the variation between the weeks. The total of this equation can then be used in the objective to minimize the variation between the weeks. Next, the changes are minimized by counting the number of weeks there is a variation in hours in Constraint (14). The used *hourvariationcount* is a binary variable to indicate whether there is a change between week t and the following week t+1. The large number M divides the total hours into a decimal amount. This then ensures the *hourvariationcount* to be either higher, thus 1, or lower, 0, if there is no change between the two weeks. This count is needed to beside the variation between weeks, also limit the amount of weeks that there is a variation. The sum of the *hourvariationcount*, is also minimized in the objective.

$$\text{weekhours}_t = \sum_{i \in A} x_{t,i} \cdot H_i \cdot \textbf{RobHours}, \quad \forall t \in T \tag{10}$$

$$\text{hourvariationweek}_t \geq \text{weekhours}_{t+1} - \text{weekhours}_t, \quad \forall t \in T \setminus \{t_{|T|-1}\} \tag{11}$$

$$\text{hourvariationweek}_t \geq \text{weekhours}_t - \text{weekhours}_{t+1}, \quad \forall t \in T \setminus \{t_{|T|-1}\} \tag{12}$$

$$\text{totalhourvariation} = \sum_{t \in T} \text{hourvariationweek}_t \tag{13}$$

$$\text{hourvariationcount}_t >= \text{hourvariationweek}_t / \text{m.M} \tag{14}$$

Calculate the start and end weeks per activity The below constraints are used to assist in the correct following of the precedence relations between models and, therefore, the production of the machine in the proper order. Furthermore, the constraints also help to determine the makespan per project. The starting and end week per activity are needed to ensure these goals. However, as the model determines the planned activities fractions based on the given objective, the starting and end weeks of the activities are not fixed. To determine these weeks based on the planned fractions, constraints (15) to (21) are introduced. First constraints (15), (16) translate the planned fractions to either ones or zeros. For this, the auxiliary 'bin' variable is introduced. If a fraction of an activity is planned in a particular week, the 'bin' variable will have a value of one for that week, zero otherwise. The introduced 'first_bin' variable takes it a step further and gets through constraints (17), (18) only a value one at the first occurrence of a planned fraction. In constraints (19), (20), the 'bin' and 'first_bin' are used to determine the first week per activity. The same is done for the last week in constraint (21). Figure 18 also visualises the above-described process. In (a), an example of planned fractions of an activity is shown; these are then translated to binary variables in (b). Next, (c) shows the first occurrence of a planned fraction used to select the first week an activity occurs (d). A similar approach is taken for the determination of the last week.

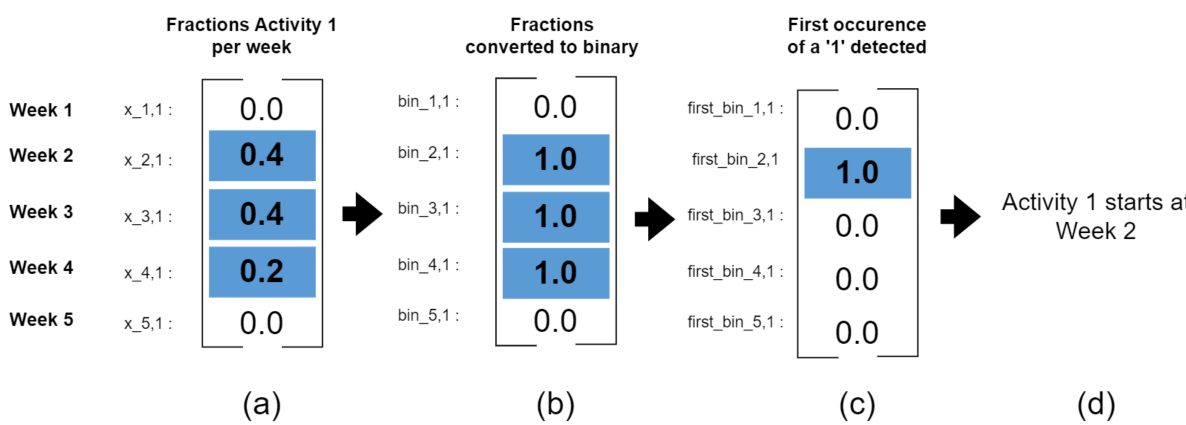


Figure 18: Determining start weeks of an activity, demonstration of Constraints (15) to (21).

$$\text{bin}_{t,i} \geq x_{t,i}, \quad \forall i \in A, \forall t \in T \tag{15}$$

$$\text{bin}_{t,i} \leq x_{t,i} \cdot M, \quad \forall i \in A, \forall t \in T \tag{16}$$

$$\sum_{t \in T} \text{first\_bin}_{t,i} = 1, \quad \forall i \in A \tag{17}$$

$$\text{first\_bin}_{t,i} \leq \text{bin}_{t,i}, \quad \forall i \in A, \forall t \in T \tag{18}$$

$$\text{firstweek}_i \leq t + (1 - \text{bin}_{t,i}) \cdot M, \quad \forall i \in A, \forall t \in T \tag{19}$$

$$\text{firstweek}_i \geq t \cdot \text{first\_bin}_{t,i}, \quad \forall i \in A, \forall t \in T \tag{20}$$

$$\text{lastweek}_i \geq t \cdot \text{bin}_{t,i}, \quad \forall i \in A, \forall t \in T \tag{21}$$

Calculate the project and activity makespan To be able to ensure relatively fast execution of a project, the project makespan needs to be determined such that it can be minimized in the objective. Constraint (22), (23) calculate per project the earliest starting and latest ending week, of which the difference in constraint (24) is summed to be able to minimize the makespan in the objective.

$$\text{lastprojweek}_p \geq \text{lastprojweek}_i, \quad \forall p \in P,\ i \in [\text{start\_index}[p-1], \text{end\_index}[p-1]+1] \tag{22}$$

$$\text{firstprojweek}_p \leq \text{firstweek}_i, \quad \forall p \in P,\ i \in [\text{start\_index}[p-1], \text{end\_index}[p-1]] \tag{23}$$

$$\text{summakespan} \geq \sum_{p \in P} (\text{lastprojweek}_p - \text{firstprojweek}_p)^2 + \text{lastprojweek}_p \tag{24}$$

$$\text{minfirstweek} \geq \text{firstprojweek}_p, \quad \forall p \in P \tag{25}$$

$$\text{maxlastweek} \geq \text{lastprojweek}_p, \quad \forall p \in P \tag{26}$$

Calculate the earliest allowed starting date per activity To ensure that a production activity does not start before its longest material lead time has passed, the sum of the estimated material lead time and the internal processing time of DIPP is used. The processing time is two weeks for a catalogue and four weeks for a custom part. Constraint (27) ensures that the time between placing the order and starting the activity equals the lead time or more. The robustness factor for material lead time slack is also used to ensure extra weeks are planned between the order time and the start of production when the parameter indicates a factor above 1.

The processing time for receiving items at DIPP does not change. Constraint (28) ensures that a material order can not be placed before the release date of that project.

$$\text{ordertime}_i <= \text{firstweek}_i - L_i \cdot \textbf{RobLeadtime} + ProcessTimePart_i, \quad \forall i \in A \tag{27}$$

$$\text{release}_p <= \text{ordertime}_i, \quad \forall p \in P, i \in [P_{start\_indexp}, P_{end\_indexp}] \tag{28}$$

Calculate the correct production order by using the precedence relations To ensure the proper order of production, the precedence relations are enforced by constraint (29) by making sure sequential activities are either planned in the same week or in a later week.

$$\text{lastweek}_i \leq \text{firstweek}_j, \forall i, j \in A, \text{ if precedence}_{ij} \geq 1 \tag{29}$$

Calculate the allowed time window to plan activities based on the release date and deadline The fractions of activities are forced to zero in weeks outside the set release date and deadline by constraint (30).

$$x_{t,i} \leq 0,\ t \geq \text{deadline}_p \,\text{or}\, t \leq \text{release}_p,\ \forall i \in [P_{start\_indexp}, P_{end\_indexp}], \quad \forall p \in P \tag{30}$$

Normalize the objective values The objective values for the model, the makespan, hour variation and hour variation count, are normalized to control their weights during solving independent of their values. The normalization is done in Constraints (31), (32) and (33) by taking the range between their minimal and maximal values and converting the actual value to a factor between 0 and 1 based on the range.

$$\begin{aligned} \min = 2, \quad \max = \text{maxlastweek - minfirstweek} \\ \text{hourvariationcount}_{norm} \cdot (\max - \min) \geq \sum_{t \in T} hourvariationcount[t] - \min \end{aligned} \tag{31}$$

$$\begin{aligned} \min = \left(\frac{\text{hour}_{\text{max}}}{\text{max\_deadline}} - \text{min\_start} + \text{leadtime}_{\text{min}} \right) \times 2 \\ \max = \text{hour}_{\text{max}} \times 2 \\ (\max - \min) \cdot \text{hourvariation}_{norm} \geq \text{hourvariation} - \min \end{aligned} \tag{32}$$

$$\begin{aligned} \min = \text{leadtime}_{\text{max}} + 1, \quad \max = (\text{max\_deadline} - (\text{min\_start} + \text{leadtime}_{\text{min}}))^2 + \text{max\_deadline} \\ (\max - \min) \cdot \text{makespan}_{norm} \geq \text{makespan} - \min \end{aligned} \tag{33}$$

Sign constraints Below, the sign constraints of the model are given.

$$\begin{aligned} \text{x}_{t,i} \in [0,1], \quad \forall t \in T,\ i \in A \\ \text{hourvariationcount}_t \in [0,1], \quad \forall t \in T \\ \text{weekhours}_t,\ \text{totalhourvariation},\ \text{totalhourvariationcount}_t, \\ \text{hourvariationweek}_t, \text{summakespan}, \\ \text{ordertime}_i,\ \text{firstweek}_i,\ \text{lastprojectweek\_ind}_p,\ \text{firstprojectweek\_ind}_p, \\ \text{minfirsweek},\ \text{maxlastweek},\ \text{lastweek}_i \geq 0, \quad \forall t \in T,\ i \in A \\ \text{bin}_{t,i},\ \text{first\_bin}_{t,i}, \in \{0,1\}, \quad \forall t \in T,\ i \in A \\ \text{hourvariation}_{\text{norm}},\ \text{hourvariationcount}_{\text{norm}}, \\ \text{makespan}_{\text{norm}},\ \text{hourvariationcount}_t \in \{0,1\} \end{aligned} \tag{34}$$

Objective Function The objective focuses on minimising the makespan of the projects, the labour hour variation between weeks and the number of weeks in which variation occurs. The weights in the objective function affect the results of the optimization. The weights selected for the projects at DIPP are shown in Appendix F.

$$\textit{Minimize} \quad \text{w\_m} \cdot \text{makespan}_{norm} + \text{w\_h} \cdot \text{hourvariation}_{norm} + \text{w\_hc} \cdot \text{hourvariationcount}_{norm} \tag{35}$$

4.4 Formulation reactive re-scheduling model

The reactive re-scheduling model is created by adapting the proactive production planning model. The re-scheduling model can be used when an unforeseen event during production affects the initially created plan. The re-scheduling model aims to assist the project manager in dealing with disruptions as best as possible. This is done by re-scheduling the order of the activities within the boundaries of the initially determined planning, taking the effect of the disruption into account. Therefore, the available regular production hours have already been fixed. When the initially selected value of the robustness parameters accounted for a slack in hours, these hours can now be used during re-scheduling. Or when slack in lead time was used, the extra weeks could ensure that no change in the planning is needed when there is a longer lead time than estimated. The model can use overtime when meeting the deadline within the planned hours is impossible. Furthermore, the model minimizes the disruptions to the original planning such that not every time there is a disruption, the entire order of activities is changed.

First, the definition and input of a disruption to the model are explained. Afterwards, the specific changes to the sets, parameters, variables, constraints, and objectives are described.

Input of a disruption A disruption to the created planning is defined as follows : [week, type, activity, effect]. The meaning of each aspect and how it is dealt with in the model is described below.

1. Week: The week in which the disruption is noticed, such as hearing that a material is delayed or finding out that a design change needs to be made that affects the duration of the production activity. The week is used to create a set of frozen weeks, including all weeks already passed. This way, the disruption can only be solved in the future weeks.
2. Activity: The activity that is affected by the disruption.
3. Type: The type of disruption: this could be labour hour or material lead time based.
4. Effect: The effect of the disruption. Used in combination with the Type and Activity to update the correct original estimate with the new value.

An example of a disruption is [2, 1, Hour, 5]. This means that in week 2 there has been an hour disruption to activity 1, the new hour estimate for that activity is 5. The update to the estimations are made before running the model, if there are multiple disruptions, multiple updates are made. The latest update will be passed to the model if two disruptions of the same type happen to the same activity. The updates of the disruptions affect the parameters H_i and L_i, which are inputs of the model and will contain the deviations needed to both the hours and lead time after disruptions.

Sets Besides the above-defined sets, a set of frozen activities is added to the model to prevent changes in the planning within these weeks. This set is used to make sure the model only optimizes the planning within the unfrozen weeks. This can be the case when a disruption happens during production, meaning that only the remaining weeks are left to solve the disruption.

FT	Set of frozen weeks $\{\text{startweek}, \ldots, \text{fixedweek}\}$

Parameters All the parameters stay the same except the two robustness parameters. As the robustness factor has already been chosen and indirectly affects the planning, these parameters are no longer needed. New parameters are also added as the re-scheduling needs to happen within the set boundaries of the above model. These boundaries are the planned week hours and the set order times. The planned fractions of activities are also given as input to the model to measure the deviation between the original planning and the re-scheduled planning. Furthermore, three new objective weights are introduced as the objective is extended with overtime, total disruption and activity makespan minimization.

fixed_weekhours$_t$	Indicating planned hours scheduled in week t, $t \in T$
fixed_ordertime$_i$	The determined order time of activity i, $i \in A$
fixed_x$_{t,i}$	Indicating planned fraction of activity i scheduled in week t, $t \in T, i \in A$
w_to, w_td, w_{am}	Weight in the objective of total overtime (to), total deviation (td) and activity makespan (am)

Variables All variables of the above model are kept as the re-scheduling can lead to new values for each. Next, new variables are introduced to measure the overtime the model uses, the deviations from the original planning and the activity makespan.

overtime$_t$	Needed overtime in week t, $t \in T$
totalovertime	Total overtime in the entire planning
xdeviation$_{t,i}$	Deviation of activity i in week t, $\forall i \in A$, $\forall t \in T$
totaldeviation	Total deviation from the original planning
activitymakespan	To define the maximum activity makespan
activitymakespan$_{norm}$	Normalization of activity makespan in objective
overtime$_{norm}$	Normalization of overtime in objective
deviation$_{norm}$	Normalization of deviations in objective

Constraints All constraints, thus Constraint 8 to 34, are the same as the model above. The only exceptions are the constraints that originally contained the robustness parameters. The multiplication with the parameters has been removed, meaning that the multiplication factor is effectively set permanently to a value of 1. Furthermore, new constraints are added to calculate the needed overtime, the deviation from the original and the fixed plan until the disruptions occur.

Calculate overtimes As the model above decides on a number of labour hours per week, these planned hours can potentially solve a disruption. Sometimes, a disruption can have such a significant effect that re-sequencing activities cannot be done within the available hours, and thus, overtime is needed. The constraints below measure the overtime required. The overtime is measured per week in constraint (36). The total sum is then calculated in constraint (37) to use as a minimization in the objective. The overtime per week is also squared to measure a negative change in hours, encouraging the model to stay within the set hours as much as possible.

$$\text{weekhours}_t = \text{fixed\_weekhours}_t + \text{overtime}_t, \quad \forall t \in T \tag{36}$$

$$\text{totalovertime} = \sum_{t \in T} overtime_t{}^2 \tag{37}$$

Calculate the fixed weeks To ensure that the model cannot make changes in weeks that have already passed, constraint 38 fixes the planned fraction of activities in the set frozen weeks. Constraint (39) ensures that there are also no changes in the planned labour hours of that week. The constraints ensure no changes can be made in the frozen weeks.

$$\text{x}_{t,i} = \text{fixed\_x}_{t,i}, \quad \forall i \in A, \quad \forall t \in FT \tag{38}$$

$$\text{weekhours}_t <= \text{fixed\_weekhours}_t, \quad \forall t \in FT \tag{39}$$

Calculate deviation made from the original planning To minimise the effect of the disruptions to the original planning, the changes made to the planning are minimized. The deviation from the initially planned fractions is tracked in constraint (40) and summed in constraint (41); again, the deviations are squared to also account for negative deviations. Furthermore, an activity should also be rescheduled compactly, such that its production is not spread over many weeks just to fit within the set boundaries, which, although it might be hour-efficient, is annoying in practice. Constraint (42) calculates the introduced activity makespan by taking the difference between the first and last week the activity is planned. The activity makespan will be used to minimise the division of the activities.

$$\mathrm{x}_{t,i} = \mathrm{fixed\_x}_{t,i} + \mathrm{xdeviation}_{t,i}, \quad \forall i \in A, \quad \forall t \in FT \tag{40}$$

$$\mathrm{totaldeviation} >= \sum_{t \in T, i \in A} xdeviation_{t,i}{}^2 \tag{41}$$

$$\mathrm{activitymakespan} \geq \mathrm{lastweek}_i - \mathrm{firstweek}_i, \quad \forall i \in A \tag{42}$$

Normalisation constraints The new objective values for the model, the activity makespan, overtime and deviations, are normalized to control their weights during solving independent of their values. The normalization is visible in Constraint (43), (44) and (45)

$$\begin{aligned} \min &= 0, \\ \max &= \mathrm{lastprojectweek\_ind}_p - \mathrm{firstprojectweek\_ind}_p, \\ \max \cdot \mathrm{activitymakespan}_{\mathrm{norm}} &\geq \mathrm{activitymakespan} \end{aligned} \tag{43}$$

$$\begin{aligned} \min = 0, \quad \max &= \mathrm{hour}^2_{\max} \cdot 1.3 \\ \max \cdot \mathit{textovertime}_{\mathrm{norm}} &\geq \mathrm{totalovertime} \end{aligned} \tag{44}$$

$$\begin{aligned} \min = 0, \quad \max &= \mathrm{total\_activities}^2 \\ \max \cdot \mathrm{deviation}_{\mathrm{norm}} &\geq \mathrm{totaldeviation} \end{aligned} \tag{45}$$

Sign constrains

$$\begin{aligned} \mathrm{overtime}_t, \mathrm{totalovertime}, \mathrm{xdeviation}_t, i, \mathrm{totaldeviation} \geq 0, \quad \forall t \in T, i \in A \\ \mathrm{activitymakespan}_{\mathrm{norm}}, \mathrm{overtime}_{\mathrm{norm}}, \mathrm{deviation}_{\mathrm{norm}}, \in \{0, 1\} \end{aligned} \tag{46}$$

Objective The original objective is to ensure the plan meets the earlier requirements. However, the objective is extended by minimizing overtime and deviation from the original planning. This way, the model is forced to solve the disruption within the boundaries set by the original planning as well as possible.

$$\begin{aligned} \mathit{Minimize} \quad & \mathrm{w\_m} \cdot \mathrm{makespan}_{norm} + \mathrm{w\_h} \cdot \mathrm{hourvariation}_{norm} + \mathrm{w\_hc} \cdot \mathrm{hourvariationcount}_{norm} \\ & + \mathrm{w\_am} \cdot \mathrm{activitymakespan}_{norm} + \mathrm{w\_to} \cdot \mathrm{overtime}_{norm} + \mathrm{w\_td} \cdot \mathrm{deviation}_{norm} \end{aligned} \tag{47}$$

The created models are validated with data from production project 1. The data is given as input to the model, and the constraints' correctness is manually verified. More information on the validation can be found in Appendix B.

4.5 Model programming

The above models have been created in Python, a standard programming language with much online documentation. Both models are programmed according to the Pyomo format. This format supports the creation of mathematical models in Python and can be linked to several solvers. For this thesis, the Gurobi solver has been chosen. Gurobi's educational license is used for the experiments. The implementation of the model at DIPP is discussed in Chapter 6.

As this thesis creates two models that need different data as input, a data structure has been designed to ensure that the models can access the data and collaborate. The project manager can add data regarding a project to a file that stores all projects that need to be planned. This data is added from the 'projects to plan' database. Projects can also be deleted from there. When project planning needs to be created, the proactive production planning model retrieves all projects from this database and creates a production plan. This planning is then saved in a separate database that stores the current planning. When a disruption occurs, the production project database is updated to incorporate the disruption effect. The reactive re-scheduling model uses the information from both databases to update the current planning. As a result of the rescheduling, the current planning is updated in the 'current planning' database. An overview is visible in figure 19.

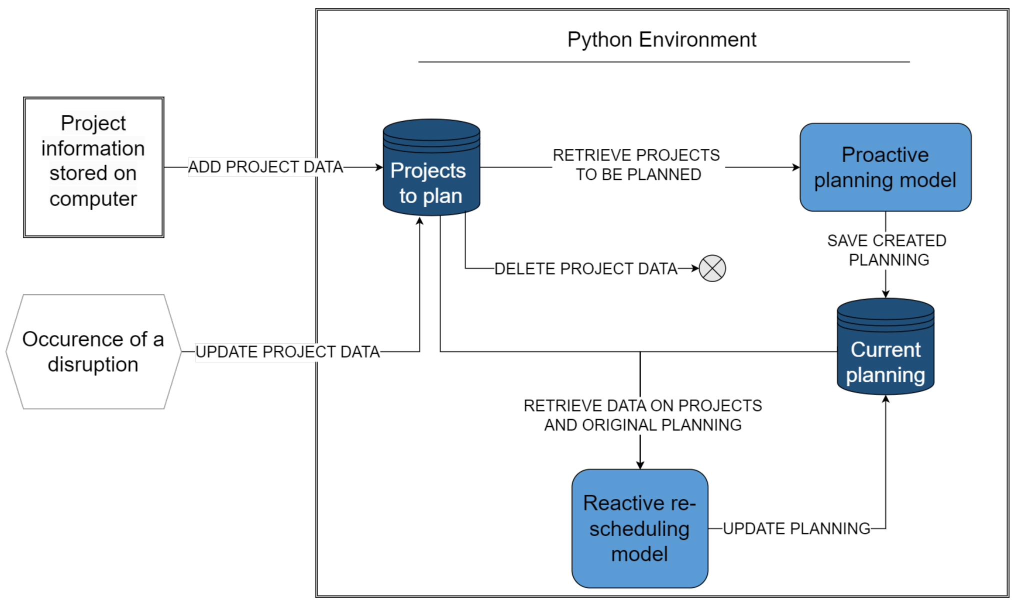


Figure 19: Data structure between models in python environment

The JSON format is chosen as a data storage format. JSON is an easy-to-parse and read format, has no further data requirements and can be adapted easily to the needed data structure. An example is shown in Figure 20. For retrieving e.g. the duration of activity one, data['project1']['hours'][1] gives the value 30.

Project information	Project in Json format

Project 1:
- Activity 1: 30 labour hours, 1 week material lead time
- Activity 2: 20 labour hours, 2 weeks material leadtime
	{
	project1: {
	hours: [
	1: 30,
	2: 20
	],
	leadtime:[
	1: 1,
	2: 2
	]
	}
	}

Figure 20: Example of the Json storage format

4.6 Conclusion

This chapter describes in detail the designs for the proactive production planning and reactive rescheduling models. It also states the assumptions for the models and how they will be programmed. The main points of this chapter are summarized below.

- The model designs are made assuming that information on the production projects is available regarding the start date, deadline, project activities, per activity, a labour hour estimate, material lead time estimate and the precedence relations between activities. The production projects, therefore, fall within the generalization made in Chapter 2.
- The proactive production planning is designed. Proactive robustness is created by a robustness factor that indicates the slack for the labour hour estimates and one for the material lead times. The model minimises the project makespan, the amount of labour hour variation between weeks and the total weeks in which variation occurs.
- A disruption has been defined as [week, type, activity, effect]. This indicates the week in which the disruption occurs, the kind of disruption, the affected activity, and the effect of the disruption. A disruption can be used to update the input from the production project information.
- The reactive re-scheduling model is designed. This is an extension of the pro-active model. Reactive robustness is created by re-scheduling within the determined labour hours, possibly including slack, which the proactive model created. Extensions to the model are made by adding the decisions from the pro-active model as parameter input, which are the determined labour hours per week, the fractions of activities planned per week and the determined order times. Disruptions that occur are processed in the model parameters input. Next, the objective is extended by minimizing the needed overtime, the activity makespan and the deviation from the original planning.
- The output of both models is a weekly-based plan that indicates the fractions of planned activities and the labour hours needed per week. The planning only starts when the material lead times of the production activities have passed.
- The models will be coded in Python according to the Pyomo format. For the experiments, the solver Gurobi will be used. A data structure has been designed so that the input and output of the models are collected and stored correctly.

5 Experiments

In this chapter, the proactive and reactive models are validated and used to evaluate three approaches to production planning. First, the available data on the two production projects and the occurrence of disruptions are analysed. Then, the set-up of the experiments and the production planning scenarios that will be used to evaluate the experiments are described. The chapter closes with a discussion of the experiment results. Therefore, this chapter answers the following research question:

How can the designed modelling approach be evaluated and validated?

5.1 Available data

This section discusses the data available at DIPP for the experiments. It contains data on the two production projects and their disruptions. Based on this data, experiments can be designed, and weights for the model's objectives can be set.

5.1.1 Data production projects

The data has been collected based on the available data at DIPP; if estimations or assumptions were made during the collection of this data, these are stated below.

Assumptions production project 1:

- Since the project is running at the time of writing, not all parts have an accurate lead time yet. Together with the purchasing department, estimations for these lead times were made.
- The configuration engineer and project manager have made the activity hour estimations. This was, however, done after the project manager had planned the production. Therefore, there might be a bias based on the planning as the hours had to fit the created planning.

Assumptions production project 2:

- The labour hour estimations for the project are made by the project manager in combination with the configuration engineer and assembly coordinator. The hour estimations are based on experience from a previous build, but these were not measured.

For each project, the data below was collected. The detailed data per project is also given in Appendix A.

- The project's name
- The project's start date, the date that the quotation needs to be drawn up. This means no materials have been ordered, and no employees have been arranged. There is, however, information on the machine's structure and the material lead times.
- The project deadline, meaning that all production activities should be finished.
- The number of the activities part of the production project.
- The hours needed to complete a production activity.
- The longest material lead time per production activity in weeks, considering whether the part is a catalogue or custom. If the part is a custom part, four weeks of internal buffer time is added; if the part is a catalogue part, two weeks of internal buffer time is added.
- The precedence relations between the production activities, indicated in a precedence matrix based on the order in which the activities need to be executed.

To ensure that DIPP can compare its current approach with the experiments, the plan created with the initial deadline is set as default. Furthermore, the data only contains the activities for both projects' assembly and integration phases. Planning this part of the production process is the most complicated since further stages, such as testing, are hard to split into separate sections.

5.1.2 Data production disruptions

The available data regarding past disruptions is studied to see how this can be used to simulate disruptions. As discussed in Chapter 2, the data on disruptions is minimal, but the available data gives insight into the range and distribution of the disruptions. This thesis uses the beta distribution to determine a distribution for both disruption types. This is a continuous probability function in the range of 0 to 1, of which two parameters can control the shape: α and β (Sugiyama, 2016). By adopting these parameters, the shape can fit the available disruption data. The range of 0 to 1 can be converted to the range of the distributions as demonstrated in Equation 48 with BV = Beta Distribution Value, UR = Upperbound range, LR = Lowerbound range. The lead time and hour disruption distributions are further designed below.

$$\text{Generated disruption factor} = (BV * (UR - LR)) + LR \tag{48}$$

Lead time disruptions
The individual lead time disruption data has been discussed in Chapter 2. Figure 21 shows the distribution for both projects combined. The lead time decreases maximally with a multiplication factor of 0.6 and increases to a factor of 1.9. Therefore, the range for generating lead time disruptions will be defined from 0.6 to 1.9. Next, the distribution needs to be fitter to a beta distribution. The distribution of lead time disruptions does not show a clear trend; since this is only disruption data on two projects, we do not want to fit the distribution too tightly as future disruptions can be different from these disruptions. As the peak of production project 1 lies at 1.4 and the peak of production project 2 is at 1.2, the beta distribution will peak at 1.3. The fit of the chosen distribution is a beta distribution with $\alpha = 2.5, \beta = 2$.

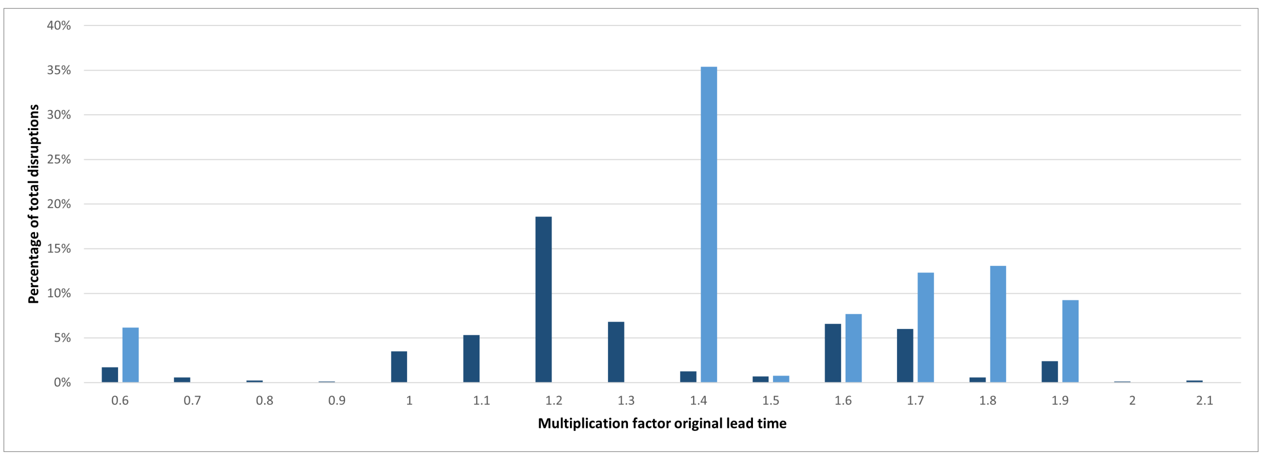


Figure 21: Distribution of lead time disruptions production projects 1 (light-blue) and 2 (dark blue) based on the available data

Hour disruptions
Chapter 2 discussed the available data of both projects on hour disruptions. The combined distributions can be found in Figure 22. With the knowledge that the hour disruptions of production project 2 miss a large proportion of the data and that project 1 only contains a few data points, no clear trend can be found. However, the range of the disruptions can be established by taking the average between the lowest factor of both projects, roughly 0.4 and the highest factor of project 1, 1.8. The total increase in hours is taken to create the distribution. This is 20 or 40 percent for projects 1 and 2, respectively. Therefore, the peak of the beta distribution will be fitter to an increase of 30 percent, thus a factor of 1.3. The chosen beta distribution fits with $\alpha = 4, \beta = 2$.

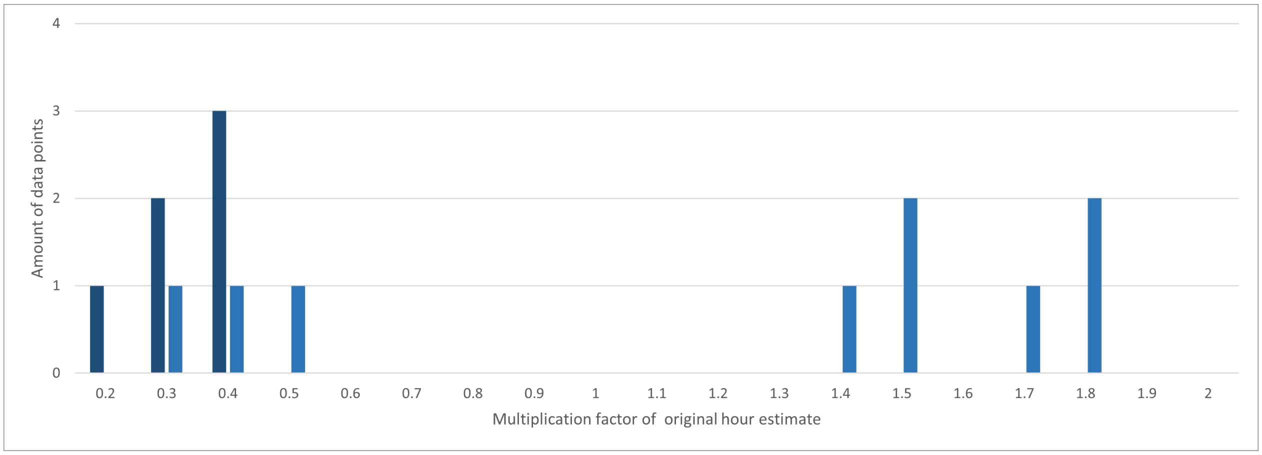


Figure 22: Distribution of hour disruptions production project 1 (light-blue) and 2 (dark blue) based on the available data

Based on the current progress at production project 1, the division between lead time and hour disruptions appears to be equally distributed. As there is no data on the division in project 2, the division of project 1 is assumed to be valid for both projects.

5.2 Experiment design

The goal of the experiments is to gain insight into how different approaches to incorporating slack into the production plan affect the plan's ability to be robust against the above-defined disruptions. Three different approaches to slack placement will be taken, and various levels of slack will be tested against increasing amounts of disruptions. This section describes the setup of the experiments and how the experimental disruptions will be generated. The performance measurement of the experiments is also described.

5.2.1 Experiment set-up

The general approach to an experiment, regardless of the type of slack placement and the scenario, consists of three steps. Each step is described in more detail below. The three steps are:

1. A production plan will be created using the proactive production planning model. Robustness will be added through various amounts and placements of hour and/or lead time slack.
2. The created plan will be tested against increasing disruptions. Updates to the plan are made using the reactive rescheduling model.
3. The robustness of the initial plan is measured by comparing it with the (additional) labour hours used after the rescheduling with disruptions.

1: Creation of a robust production plan The experiments will test three robustness tactics. Each of the three experiments will incorporate labour hours and/or material lead time slack in another way. Figure 23 demonstrates the different options for slack placement. The top left shows a basic production planning scenario where regular labour hours are equally spread over two production weeks. The deadline is also indicated. To incorporate lead time slack into the model, indicated on the bottom left of the figure, extra time could be taken before the start of the production to give the materials more time to arrive on time. Labour hour slack can be incorporated in three different ways, represented in the three experiments:

Experiment 1: Equal slack division over production activities. The plan will incorporate slack based on a multiplication factor of the original labour hour and materials lead-time estimates. The created slack will be considered in the planning, moving the plan forward and determining the number of extra hours added on top of the production weeks, as in (1) in Figure 23.

Experiment 2: Proactive slack approximation. The incorporated amount of slack will be based on the average demand for slack for a certain number of disruptions. This can lead to an uneven spread of slack, depending on the bottlenecks of the plan and the disruptions. The slack placement can, besides lead time, affect the number of planned hours as in (2) in Figure 23.

Experiment 3: Slack placement at the end. Slack placement after the last week of production; otherwise, if not possible, it will be on top of the last production week. Like the equal division experiment, the amount of slack will depend on a factor of the original labour hours. This approach is visualised at (3.1) and (3.2) in Figure 23. It can also be combined with lead time slack.

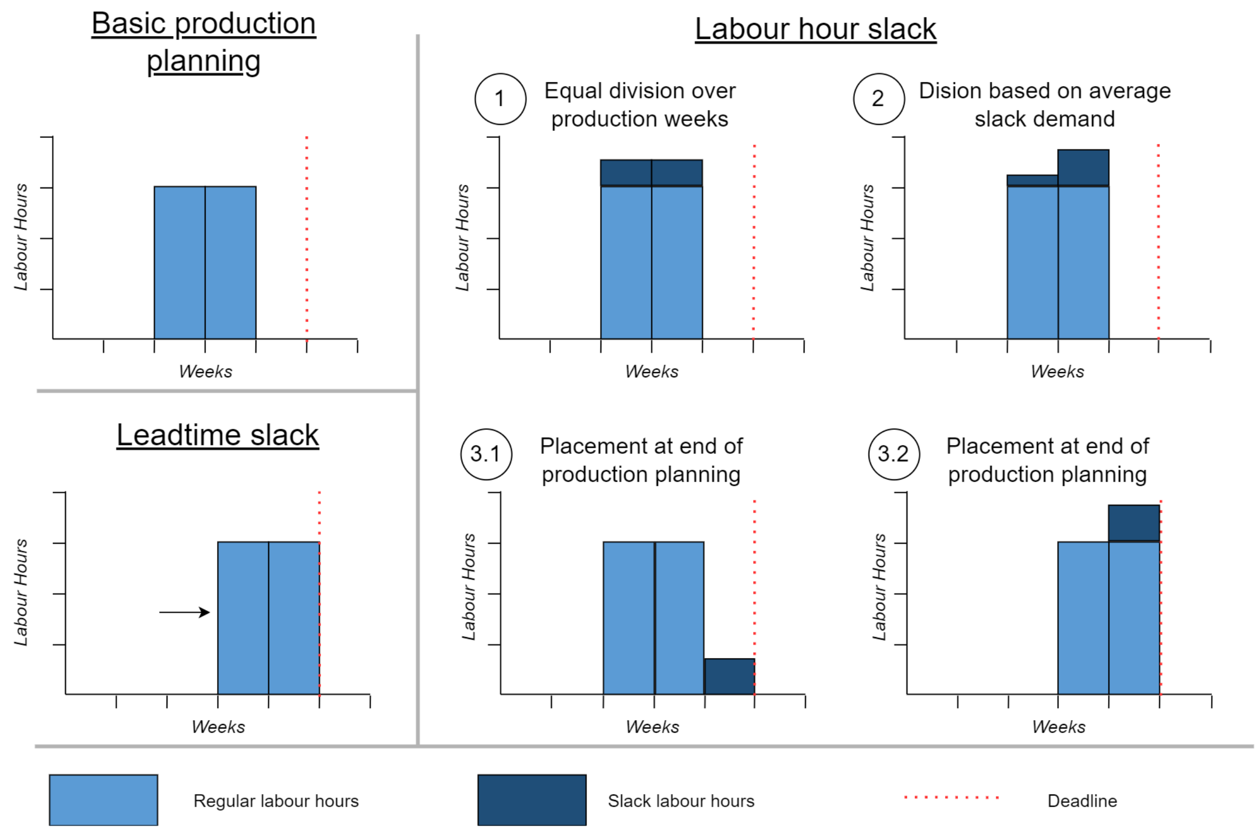


Figure 23: Different methods to incorporate slack in production planning.

2: Generating disruptions The different slack placements in the three experiments must be tested against disruptions. The disruptions are generated following the standard set in Chapter 4, thus as [week, activity, type, effect]. This means a disruption is set to occur in/after a particular week, be of a specific kind, affect an activity and result in an adaption of a data value because of the disruption. Each aspect is generated differently:

Week: The week indicates the week up until the schedule is fixed; thus, rescheduling can only happen after that week. The experiments' week is set at the first production week, meaning the entire schedule can change. This is done because all lead time and hour estimations can be disrupted during the experiments. When a later week is chosen, a selected disruption might be within the fixed weeks, and the model will give an unfeasible result.

Activity: The disruption affects a specific production activity, randomly selected from the list of all activities.

Type: This thesis looks at two types of disruptions: hour and lead time. Therefore, the kind of disruption has been encoded to 0 (lead times) or 1 (hour). The type is chosen depending on the experiment scenario.

Effect: The combination of a type of disruption and module leads to the change of a specific data value. For example, a labour hour disruption for an activity means that the estimated initial hours must change. A new value is generated based on the beta distribution established in section 5.1.

For example, take a production project with two activities, both taking ten hours, having a lead time of one week, and a deadline after 2 weeks. A generated disruption for the project could be [1,1,1,11]. This means that the disruption occurs in week one, affects the estimated labour hours since it is of type 1, affects activity 1, and gives a new estimation of 11 hours. The original value of the hours for activity 1 was 10, so this specific disruption increased the needed hours by 10 percent.

The generated list of disruptions is used to modify the input of the rescheduling model. This is done by adapting the input of the hour and lead time estimates for the activities with the new updated value of the disruptions. After all disruptions have been processed, the model can run with the latest hour and lead time values.

3: Measuring effect of robustness The performance of each experiment will be measured in the same way. Each unique combination of slack quantity, placement, and number of disruptions in an experiment will be repeated 20 times. The average number of hours needed is taken from the 20 repetitions and compared with the planned hours. In the case of hour disruptions, the change is visible by the increase or decrease in the total hours needed to finish production. However, in the case of a lead time disruption, the movement of the production plan does not affect the total hours required to finish production. Therefore, the originally planned hours are also kept in place but are noted as unused. This is also realistic as employees most likely have been arranged for the initially planned weeks and, therefore, also need to be paid. Based on this assumption, comparing the initial and total hours required after a disruption can only indicate increased hours. The total costs, of which the rates are established in Chapter 2, are also used for comparison. An initially planned hour costs 100, the first two hours of overtime cost 124, and further overtime costs 141 euros. The same rate is used for both projects for fair comparison. In total, the performance comparison is done on three points:

1. The amount of additional hours needed to incorporate the disruptions.
2. The number of hours planned but unused. This means that hours were planned for a week but can not be used, e.g., because of a delay in the schedule.
3. The total costs of the project, incorporating the regular hour rate for the initially planned hours and the overtime hour rates for the additional hours.

The specific steps per experiment are described in Appendix D.

5.2.2 Experimental scenarios

Each of the three experiments will be tested against various production planning scenarios. The first two scenarios are designed to gain better insight into the relationship between a type of slack and its corresponding type of disruption. Next, four realistic production planning scenarios are designed to test the effect of slack on these scenarios. Each scenario is defined by a basic production plan on which the experiments will be conducted; it does not contain any slack and is based on the initial hour and lead time estimates given in Appendix A. The different scenarios are described below, and their basic production plans can be found in Appendix C; the specific model settings used for these scenarios are described in the next section: numeric values experiments.

Scenario 1: Effectiveness hour slack. This scenario tests the quantity and placement of hour slack against disruptions of type hour. Its goal is to provide insight into the usefulness of the hour slack.

Scenario 2: Effectiveness lead time slack. This scenario tests the quantity and placement of lead time slack against disruptions of type lead time. Its goal is to provide insight into the usefulness of lead time slack.

Scenario 3: Single production project 1. This scenario tests different quantities and placements of both slack types against both disruptions types on production project 1, giving insight into the effect on a small project.

Scenario 4: Two instances of production project 1. This scenario tests different quantities and placements of both slack types against both disruptions types on simultaneous production of two projects 1, giving insight into the possible effect of slack combination between identical projects.

Scenario 5: Single production project 2. This scenario tests different quantities and placements of both slack types against both disruptions types on production project 2, giving insight into the effect on a large project.

Scenario 6: Combination production project 1 and 2. This scenario tests different quantities and placements of both slack types against both disruptions types on simultaneous production of projects 1 and 2, giving insight into the effect of combining different projects.

Table 5 also visualises the scenario set-up.

Inclusion of:	**Scen 1**	**Scen 2**	**Scen 3**	**Scen 4**	**Scen 5**	**Scen 6**
Hour slack	x		x	x	x	x
Lead time slack		x	x	x	x	x
Hour disruptions	x		x	x	x	x
Lead time disruptions		x	x	x	x	x
Production project 1	x	x	x	x (twice)		x
Production project 2					x	x (twice)

Table 5: Overview of slack type, disruption type and production projects that are used in each scenario

5.2.3 Numeric values experiments

Each combination of a scenario and experiment requires a range of slack, the number of disruptions, the increments in which the ranges are evaluated, and the number of repetitions per unique combination. Furthermore, the model settings need to be determined for the specific scenarios.

Model settings
To set the weights of the objectives in the model, the timeline of the projects needs to be determined first. The original deadlines for completion of the production activities are set close to the arrival of the last materials, meaning there is little room to incorporate slack before the deadline. As we want to test a production plan's ability to deal with disruptions in a wide range, we will determine the project's deadline for the experiments based on the extreme disruption cases. These extreme cases are generated by taking the lowest and highest values of the disruption ranges and multiplying them with the original labour hour and lead time estimates. This leads to the extreme 'best deviations' and 'worst deviations'. The comparison of these scenarios against the original plan of Demcon is given in Figure 24. In the figure, a constant production makespan of 2 weeks is set. In the best case, the project will be finished within ten weeks, totalling 47.2 hours. In the worst case, the project takes 21 weeks and 212.4 hours, which could be shortened to 20 weeks if all the hours are planned in one week. While these are extremes, the model should be able to create a plan when the edge cases of disruptions are selected. Therefore the deadline for production project 1 is set 20 weeks after the ordering of materials for all experiments.

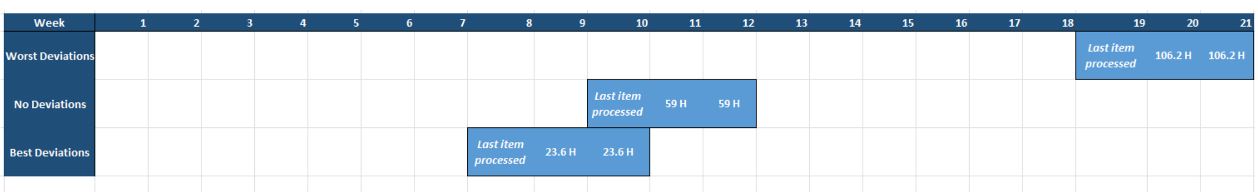


Figure 24: Analysis best and worst deviation cases Production Project 1

A similar analysis is done for production project 2. Taking a production timespan of seven weeks, as in the original planning, a scenario without disruptions would finish the activities after 34 weeks of material ordering. The best disruption case finishes after 23 weeks, and the worst after 52 weeks. Again, the worst case could be shortened by adding more hours into one week. Therefore, the deadline for production project 2 is 50 weeks after ordering materials.

The project deadline affects the model's outcome since the makespan normalization is based on the maximum available weeks to create a plan. The weights in the objective have been adapted for the experiments to these unique extended deadlines. The experiments have more room to adjust the planning, but the basic scenario should be the same as with a tight deadline. Therefore, the weight of the makespan objective is increased, and the makespan of a project is kept the same as with a small deadline. The detailed weights are in appendix F.

Ranges disruptions
A pre-analysis determines the disruption ranges over which the experiments will run. The impact of an hour of disruption on an activity can be seen in the sum of the total number of hours, which can give a rough idea of the ranges needed.

For the hours of both production projects, increasing amounts of hour disruptions are generated, and their effect on the total number of hours is plotted. As the disruptions are generated randomly, a high average of 100 iterations per disruption amount will be taken to compensate for the randomness. Figures 25 and 26 show the results and indicate that the effect on the total hours stabilizes after a while for both projects. This is because the increasing number of disruptions no longer further affects the total hours after a certain point. For production project 1, this is around 30 disruptions; for production project 2, this is around 120. Based on this, the disruption range against which the projects will be tested will be 0-30 and 0-120. As production project 1 consists of ten activities and project 2 of 43, these ranges will most likely cover the extreme case that each disruption is affected in both hours and lead time. As noted in the graphs, total hours still seem to vary despite the high repetition factor of 100. Therefore, disruptions will be sampled at non-consecutive points to see the general trend in the experiments without much effect of the individual changes.

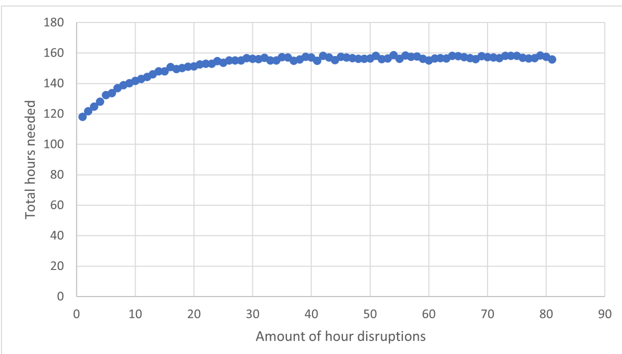


Figure 25: Effect hour disruption on total hours project 1 (n=100), total of 10 production activities

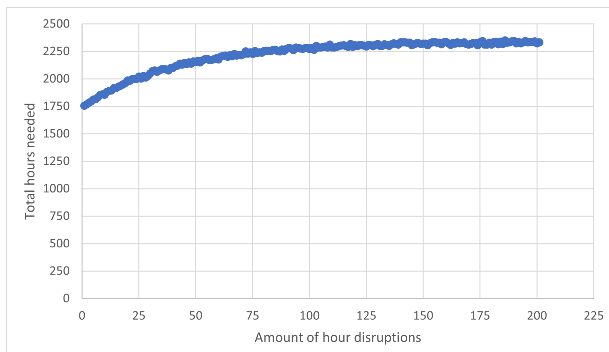


Figure 26: Effect hour disruption on total hours project 2 (n=100), total of 43 production activities

Ranges slack
The hour and lead time disruptions can have a maximum increase factor of 1.8 and 1.9. Therefore, to include all possible options, these factors will first be used to assess the effect of slack. These wide ranges will, therefore, be used for the first two scenarios, evaluating the direct relation between hour slack and hour disruptions and the same for lead time. Based on the results, the promising ranges of slack will be used in the remaining four scenarios.

Repetition factor
To compensate for randomness and keep the run length doable, a repetition factor of n = 20 is chosen for all unique settings in a run.

The conclusion of the above-discussed experimental values is shown in the below Figures 6, 7 and 8. The first figure presents the factors for Experiment 1. All values are given for scenarios 1 and 2; the others will be partially determined based on their results.

	Robustness Hours	Robustness Lead time	Robustness Increments	Disruptions	Increments Disruptions
Scen 1	1.0 - 1.8	1	0.1	0 - 30	5
Scen 2	1	1.0 - 1.9	0.1	0 - 30	5
Scen 3	TBD	TBD	0.1	0 - 30	5
Scen 4	TBD	TBD	0.1	0 - 30	5
Scen 5	TBD	TBD	0.1	0 - 120	20
Scen 6	TBD	TBD	0.1	0 - 120	20

Table 6: Values of robustness factors and number of disruptions used during Experiment 1

Experiment 2 determines the slack based on the average demand for a certain number of disruptions. Therefore, no specific input regarding the slack is needed.

	Disruptions	Increments Disruptions
Scen 1	0 - 30	5
Scen 2	0 - 30	5
Scen 3	0 - 30	5
Scen 4	0 - 30	5
Scen 5	0 - 120	20
Scen 6	0 - 120	20

Table 7: Number of disruptions used during Experiment 2

Experiment 3 determines the hour and lead time slack based on the hour and lead time factors, as in Experiment 1. However, the hour slack is placed at the end of the production project instead of being equally divided over the production weeks. The lead time slack, however, still works the same. Therefore, scenario 2 is excluded from this experiment as the approach is identical to that in Experiment 1.

	Robustness Hours	Robustness Lead time	Robustness Increments	Disruptions	Increments Disruptions
Scen 1	1.0 - 1.8	1	0.1	0 - 30	5
Scen 2	-	-	-	-	-
Scen 3	TBD	TBD	0.1	0 - 30	5
Scen 4	TBD	TBD	0.1	0 - 30	5
Scen 5	TBD	TBD	0.1	0 - 120	20
Scen 6	TBD	TBD	0.1	0 - 120	20

Table 8: Values of robustness factors and number of disruptions used during Experiment 3

5.3 Experiment Results

In this section, the results from the above-defined experiments will be given. First, the results for scenarios 1 and 2 will be provided. Based on these, the final configuration for the following scenarios will be defined, and their results will be presented. Secondly, a comparison between the scenarios will be provided.

The results of all scenarios and experiments will be presented in terms of costs for the needed hours, incorporating the costs of a regular hour and overtime. As each identical case in an experiment is repeated 20 times, the average costs over these experiments will be given. Figure 9 provides a cost baseline. This baseline includes the total hours that need to be planned for each scenario and the total costs using the regular hour rate. No slack is included in these calculations.

The slack factors used in the experiments will be presented as H = $FactorHours$ and L = $FactorLeadtime$.

Scenario	Amount of hours	Baseline costs
1	118	€ 11800
2	118	€ 11800
3	118	€ 11800
4	236	€ 23600
5	1754	€ 175400
6	1990	€ 199000

Table 9: Baseline labour hour costs without any slack for each scenario

Results scenario 1: Effectiveness hour slack The experiments conducted for scenario 1 reveal the relationship between the incorporation of labour hour slack and its robustness against labour hour disruptions. The results for experiment 1, equal slack placement over all production activities, are given in Figure 27. The figure shows the additional hours needed based on the slack incorporated and the number of hours that end up unused. A decreasing amount of extra hours is needed in the range of a slack factor of 1 - 1.3. In the range of 1.1 - 1.8, there is an increasing number of unused hours.

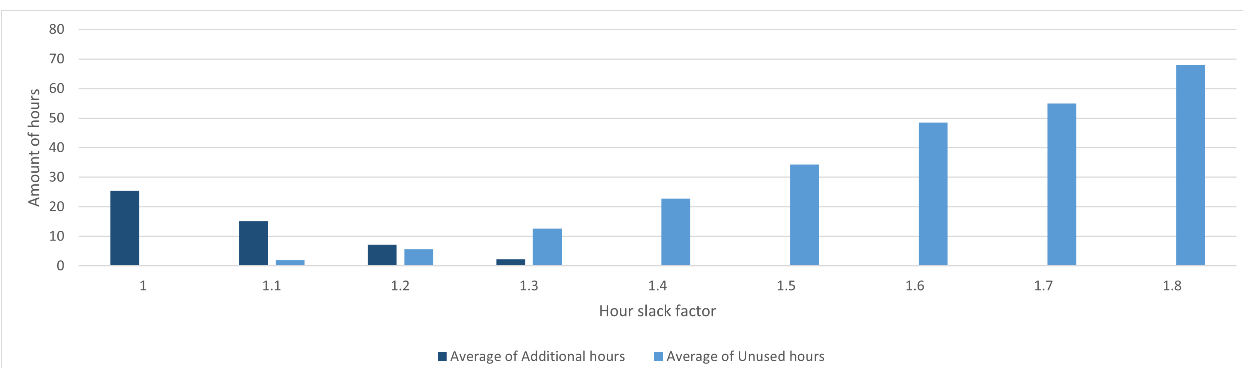


Figure 27: Effect of incorporating equally placed hour slack against hour disruptions over the weeks of production project 1

The total costs for each experiment 1 to 3 are presented in Tables 10 to 12.

As confirmed by Figure 27, the total costs from slack factor 1.4 onward appear unaffected by the number of disruptions. For factors 1 - 1.3, the needed costs increase while disruptions increase. As the starting costs per factor differ, incorporating more slack does not indicate the best approach. Table 10 shows that a factor of 1.2 is the best approach against hour disruptions when using equally spread hour slack. The second experiment tested the proactive placement of slack by taking the average over the demand for hour slack with increasing hour disruptions. Table 11 shows the total costs per disruption. The total costs increase when more disruptions occur.

Disruptions	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
0	€ 11800	€ 12980	€ 14160	€ 15340	€ 16520	€ 17700	€ 18880	€ 20060	€ 21240
5	€ 13999	€ 15179	€ 14160	€ 15340	€ 16520	€ 17700	€ 18880	€ 20060	€ 21240
10	€ 15766	€ 16946	€ 14539	€ 15719	€ 16520	€ 17700	€ 18880	€ 20060	€ 21240
15	€ 16500	€ 17680	€ 15396	€ 16576	€ 16520	€ 17700	€ 18880	€ 20060	€ 21240
20	€ 16351	€ 17531	€ 16145	€ 17325	€ 16564	€ 17700	€ 18880	€ 20060	€ 21240
25	€ 16562	€ 17742	€ 15911	€ 17091	€ 16567	€ 17700	€ 18880	€ 20060	€ 21240
30	€ 16481	€ 17661	€ 15739	€ 16919	€ 16520	€ 17700	€ 18880	€ 20060	€ 21240

Table 10: Total cost for production project 1 based on the amount of equally spread hour slack and amount of disruptions

Disruptions	
0	€ 11800
5	€ 13603
10	€ 14783
15	€ 15620
20	€ 15975
25	€ 16243
30	€ 16521

Table 11: Total cost for production project 1 per amount of disruptions based on proactively defined hour slack

In the last experiment, the placement of slack at the end of the production plan is tested. Table 12 shows the total costs per slack factor and number of disruptions. Interestingly, there is a continued cost increase, and no stabilization has been found. This can be explained by looking at the objective of the rescheduling model. By incorporating a minimization of plan deviations, the model is not encouraged to move activities to a later stage in the planning, and the model chooses to incorporate extra hours. When this objective is removed, the results are similar to that of experiment 1, with equal slack placement. Because we want to keep the disruptions to the plan to a minimum, the disruption minimization is kept in the objective. Therefore, in this case, no incorporation of end-slack is the cheapest option.

Disruptions	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
0	€ 11800	€ 12980	€ 14160	€ 15340	€ 16520	€ 17700	€ 18880	€ 20060	€ 21240
5	€ 14023	€ 14907	€ 16367	€ 15904	€ 16832	€ 17899	€ 18891	€ 20062	€ 21240
10	€ 15454	€ 16486	€ 16711	€ 16640	€ 17115	€ 18422	€ 19301	€ 20126	€ 21240
15	€ 15965	€ 17481	€ 16855	€ 17468	€ 18149	€ 18969	€ 19476	€ 20172	€ 21240
20	€ 17067	€ 17793	€ 17269	€ 17283	€ 17833	€ 20001	€ 19576	€ 20385	€ 21375
25	€ 16920	€ 18175	€ 17752	€ 17630	€ 18663	€ 19259	€ 20557	€ 20409	€ 21361
30	€ 16807	€ 18587	€ 17796	€ 17924	€ 18358	€ 19491	€ 19970	€ 20342	€ 21301

Table 12: Total cost for production project 1 per amount of disruptions based on the slack incorporated at the end and amount of disruptions

As a comparison between the different slack placement approaches, the cheapest option of each experiment is shown in Figure 28. The end slack and proactive slack start at the same total costs for zero disruptions. For the equal slack, an investment is needed at the beginning. When disruptions increase, the proactive and equal slack approach appears to be working the best. The end slack, which is essentially the plan without any slack, approach performs the worst.

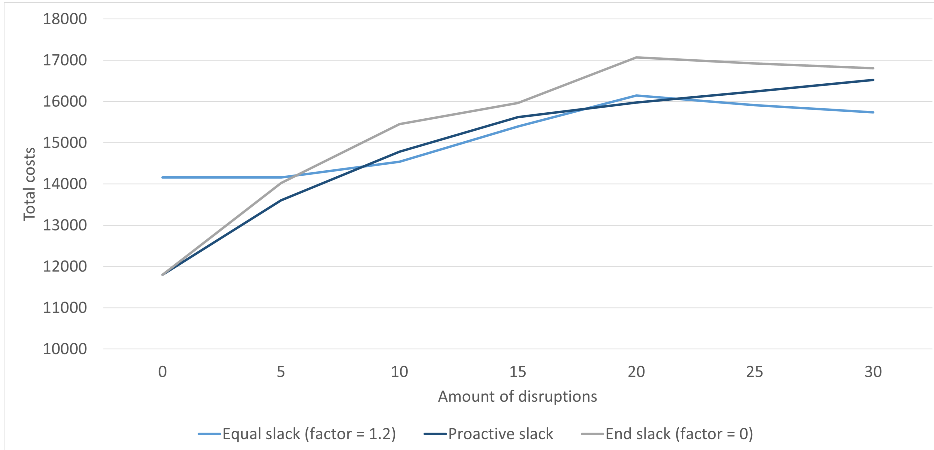


Figure 28: Comparison of cheapest total costs for different hour slack placement tactics

Results scenario 2: Effectiveness lead time slack The experiments conducted for scenario 2 reveal the relationship between lead time slack and its robustness against lead time disruptions. The results for experiment 1, equal lead time slack placement overall activity lead times, are shown in Figure 29. The needed additional hours show an apparent decrease when the lead time slack increases. The unused hours also follow this trend as a lead time disruption does not lead to more production hours being needed.

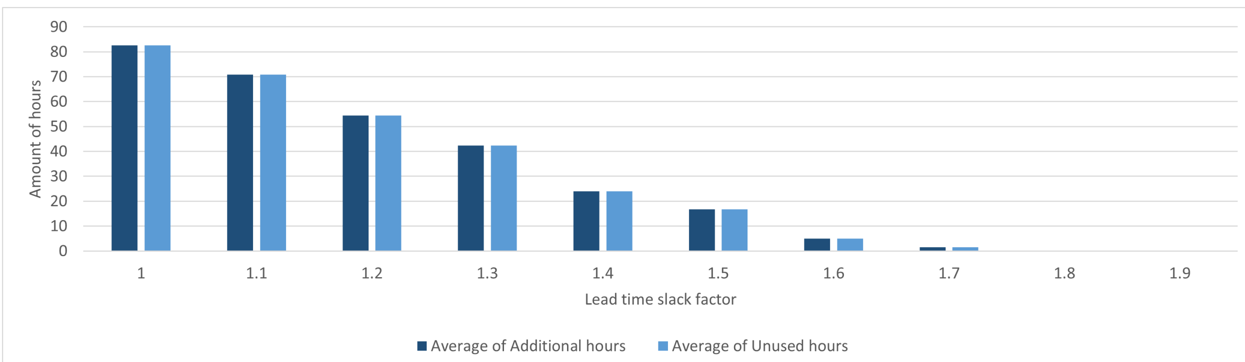


Figure 29: Effect of incorporating equally distributed lead time slack against lead time disruptions for production project 1

Tables 13 and 14 show the total costs for the experiments 1 and 2. For experiment 1, the total costs needed decreased while more slack was incorporated. This is because incorporating more lead time slack is not penalized by the model. The case of lead time slack with a factor of 1.8 is, therefore, the cheapest, but this is less desired as a client would have to wait much longer on its product. Therefore, the slack factors of 1 - 1.6 are more interesting as they demonstrate an actual trade-off between additional costs and postponing production. Table 14 shows the costs needed for the proactive placement of slack. In general, the needed costs increase when more disruptions occur.

Disruptions:	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
0	€ 11800	€ 11800	€ 11800	€ 11800	€ 11800	€ 11800	€ 11800	€ 11800	€ 11800	€ 11800
5	€ 22010	€ 21573	€ 15793	€ 15009	€ 15707	€ 13923	€ 12697	€ 11965	€ 11800	€ 11800
10	€ 25732	€ 24089	€ 19239	€ 17625	€ 14226	€ 12697	€ 12791	€ 11800	€ 11883	€ 11800
15	€ 25852	€ 22252	€ 20459	€ 22623	€ 14924	€ 14478	€ 12325	€ 12161	€ 11800	€ 11800
20	€ 25854	€ 23575	€ 22947	€ 17625	€ 16172	€ 15108	€ 12979	€ 11800	€ 11800	€ 11800
25	€ 26746	€ 23878	€ 22635	€ 19648	€ 16884	€ 15479	€ 12607	€ 12048	€ 11800	€ 11800
30	€ 25912	€ 25119	€ 23168	€ 19789	€ 16405	€ 15492	€ 12048	€ 12325	€ 11800	€ 11800

Table 13: Total cost for production project 1 based on the amount of equally lead time slack and amount of disruptions

Disruptions	
0	€ 11800
5	€ 17902
10	€ 17926
15	€ 17398
20	€ 17141
25	€ 16359
30	€ 1892

Table 14: Total cost for production project 1 per amount of disruptions based on proactively defined lead time slack

To compare both slack placement tactics, the cheapest options of both experiments are included in Figure 30. As the factor of 1.8 for equal slack placement gives an optimistic case without considering the needed wait, the factor of 1.4 is also included in the graph to put the proactive approach more in context. This factor seems to perform better or equally as well as the proactive placement tactic.

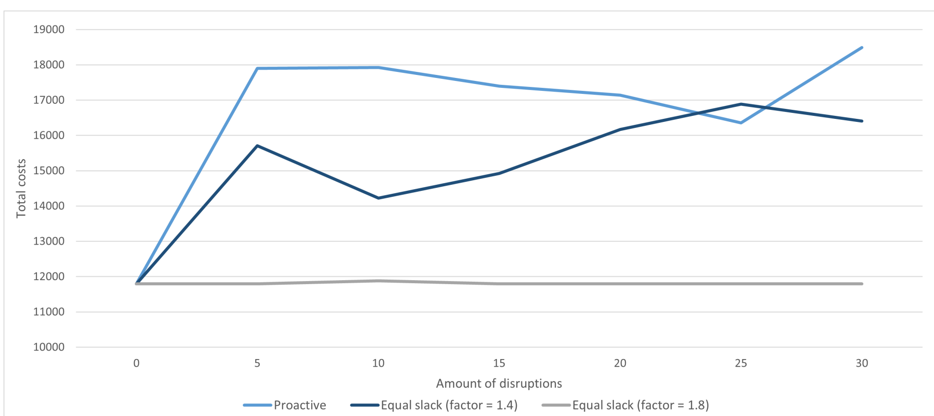


Figure 30: Comparison of cheapest total costs for different lead time slack placement tactics

Settings scenario 3-6 Scenarios 1 and 2 indicate promising ranges for hours and lead time slack to research further. For hour slack, the factor range of 1.0 - 1.3 appears to be the most effective; higher factors only result in unused hours. For lead time slack, the costs decrease when a higher factor is selected and stabilize from 1.7 -1.8 onward. Essentially, these factors make for the best option against lead time disruptions. However, a factor range of 1.0 - 1.6 will be used for lead time slack in further experiments to find a trade-off between postponing production and incurring more costs.

Results scenario 3: Single production project 1 The results of experiment 1 for scenario 3 are shown in Figure 31. The total average cost over all disruption amounts is given per lead time slack factor and hour slack factor. A downward trend in cost can be seen when the lead time slack increases. This aligns with the results from Scenario 2, which indicated that more lead time slack results in lower overall cost. The number of hour slack increases the average total cost since the higher slack factors are above the lower ones. Therefore, interestingly, the incorporation of no hour slack (H = 1) appears to be the most cost-effective option, this is however in contrast to the results from scenario 3, where an increase in hour slack indicated a lower total cost.

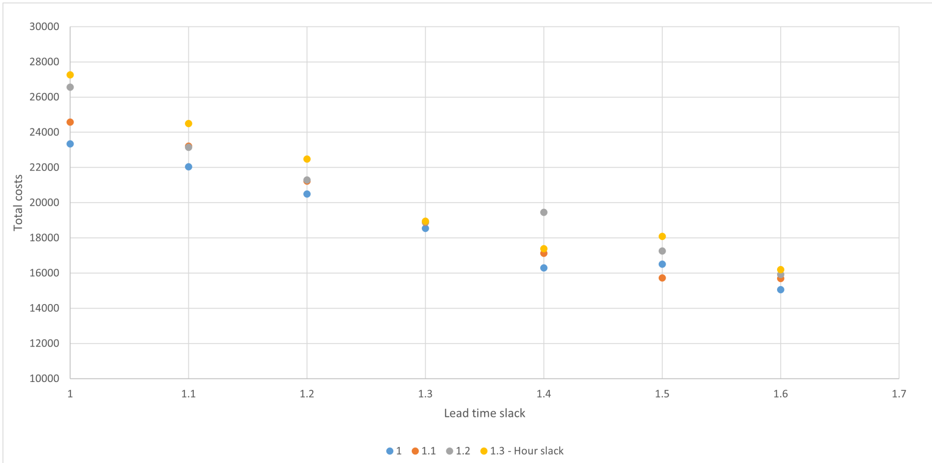


Figure 31: Indication total cost for production project 1, experiment 1, based on the amount of lead time slack and hour slack

To explain why the hour slack does not appear to be working in experiment 1, the results for a lead time slack factor of 1.3 are compared with having no hour slack and having a factor of 1.3 slack in Figure 32. The figure shows that for the incorporation of hour slack (H = 1.3), the amount of additional hours needed is much lower than when no hour slack is incorporated, meaning that the extra hours are used to solve the hour disruptions. However, as different to the results in scenario 1, the lead time disruptions create a high amount of unused hours which are counted towards the total cost. This amount of unused hours appears to be higher for the H = 1.3. This is because the additional planned hours are also unused when a lead time disruption occurs, leading to a higher amount of unused hours. Taking the additional costs to plan these extra hours into account, the higher cost for more hour slack in Figure 31 are explained.

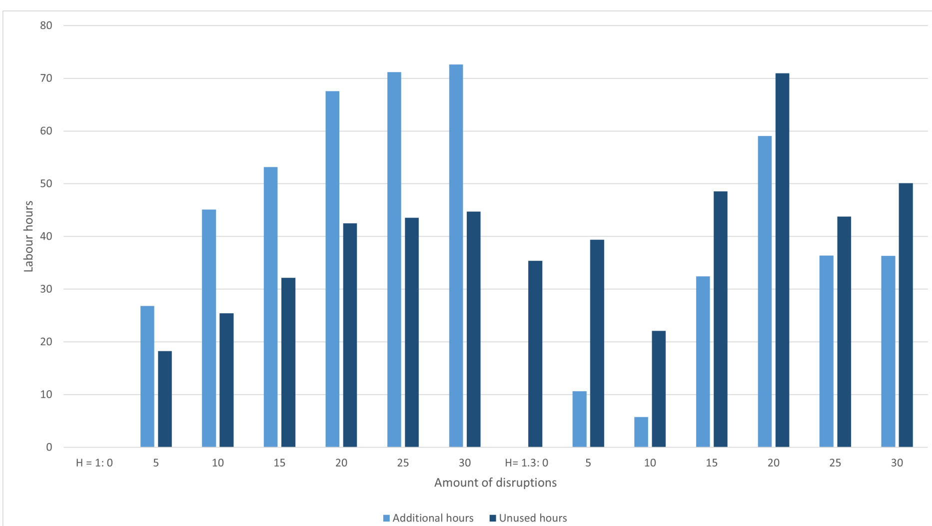


Figure 32: Amount of additional hours and unused hours in a scenario with lead time slack factor 1.3 and hour slack factor 1.0 (left) and 1.3 (right) for production project 1

Continuing on the statement that hour slack, in combination with lead time disruptions, only causes more costs, we should be able to see a trend of increased usefulness of hour slack when the lead time slack goes up. This trend is visible in Figure 31, as the dots that indicate the hour slack appear to get closer while more lead time slack is included. After a lead time slack factor of 1.3 the increase in cost is not directly related to the amount of hour slack, possibly confirming this relation.

The results for experiment 2, the proactive slack incorporation, indicated increased costs when more disruptions happen. The results for experiment 3, with hour slack placement at the end, indicate that not incorporating hour slack is the cheapest option, combined with a lead time slack factor of 1.4. This is again because the model penalizes disruptions above using the end-hour slack. Therefore, the results of experiment 3 do not provide additional value compared to experiment 1.

To place the costs of all experiments into perspective, they are compared with the L = 1.3 and H = 1.3 scenarios from experiment 1 in Figure 33. All three experiments indicate an increase in costs when more disruptions occur. Incorporating lead time slack without any hour slack is the cheapest option, the selected equal slack placement is the second most affordable, and the proactive approach appears to be the most expensive.

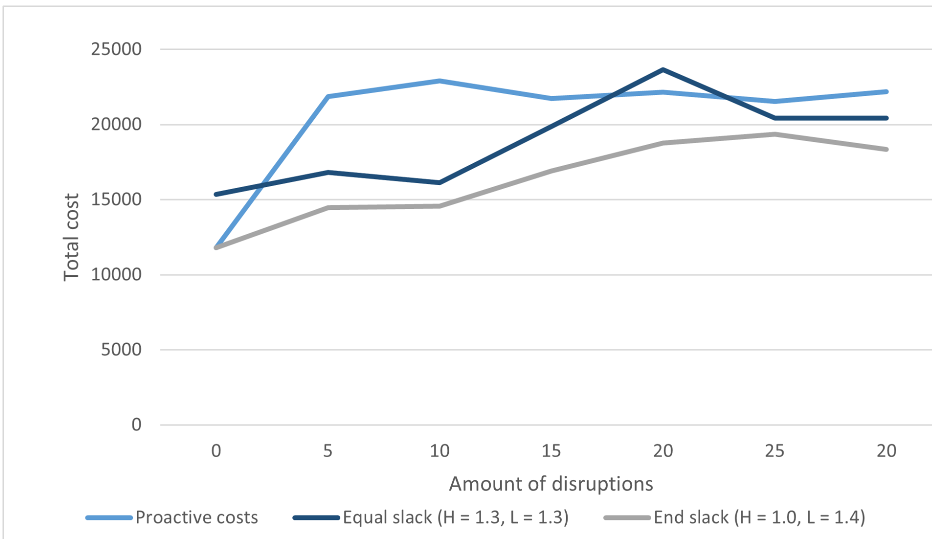


Figure 33: Total cost comparison production project 1 between different slack scenarios

Results scenario 4: Two production projects 1 The results for scenario 4, experiment 1, are visualized in Figure 34. The trend in the graph appears to be similar to scenario 3: the downward trend in cost when more lead time slack is added and the uselessness of hour slack when the lead time slack is low. The lowest cost is at a lead time slack factor of 1.4 and an hour factor of 1.2. Looking at the graph, this does appear to be deviating from the general trend of the dots, which is why this low cost could be due to a lucky generation of disruptions.

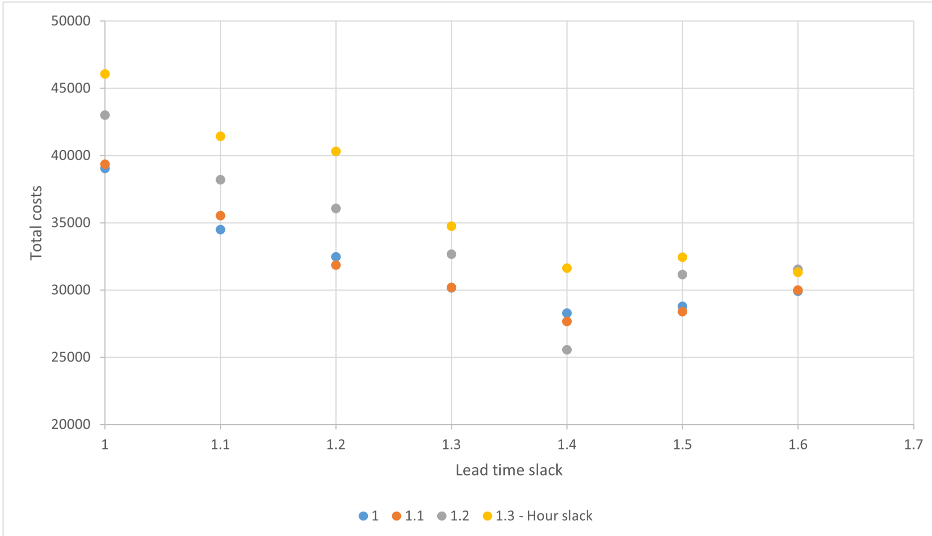


Figure 34: Indication total cost for two planned production projects 1, experiment 1, based on the amount of lead time slack and hour slack

As in the trend with the other scenarios, the end slack indicates no benefit against disruptions, and the proactive approach gradually increases costs when more disruptions occur. Both slack placements are compared to the cheapest setting of experiment 1 in Figure 35. The proactive approach appears to work similarly to the equal slack placement approach, but as it fits its slack towards the number of disruptions, the initial cost is lower. Again, a scenario with no end-hour slack and a lead time factor 1.4 is the cheapest option.

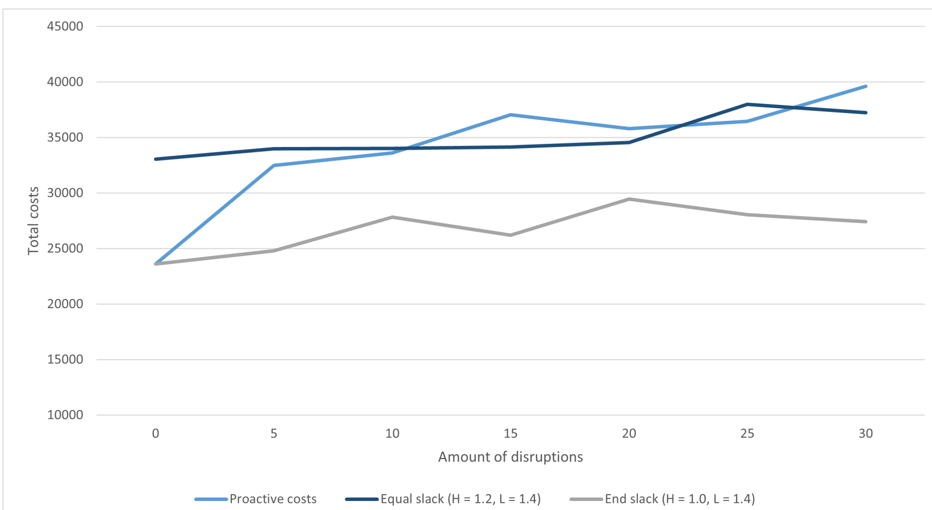


Figure 35: Total cost comparison two production projects 1 between different slack scenarios

Results scenario 5: Single production project 2 The results for scenario 5, experiment 1, are presented in Figure 36. Similar to the scenarios with production project 1, there is a downward trend of average total costs when the lead time slack factor increases. Compared with Figure 31 and 34, the costs also appear to stabilize in all scenarios after a slack factor of 1.4. However, the hour slack appears to have a more significant impact on the total cost. So do the factors 1, 1.1, and 1.2 lie closely together at the start, and do 1.1 and 1.2 appear to work better towards the end.

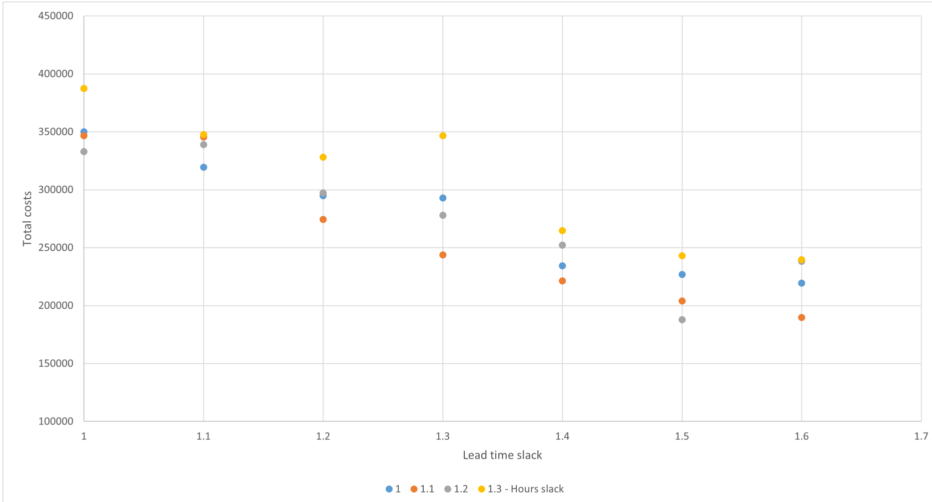


Figure 36: Indication total cost for production project 2, experiment 1, based on the amount of lead time slack and hour slack

The costs of the proactive approach are again compared with the results from the first experiment. The above scenarios indicated that the placement of end slack does not work in the chosen experiment set-up, and it is always the cheapest with no-hour slack incorporated. Therefore, instead of running it separately, the results from experiment 1 with no hour slack are taken. The comparison between the proactive determination of slack, the most promising scenario of experiment 1 and a scenario without slack is done in Figure 37. The figure shows the proactively determined slack following the same trend as the above scenarios, where its costs are the most expensive. Next, the scenarios with and without hour slack, for a lead time factor 1.5, are comparable. The hour slack works slightly better than no-hour slack, but the initial investment costs are higher.

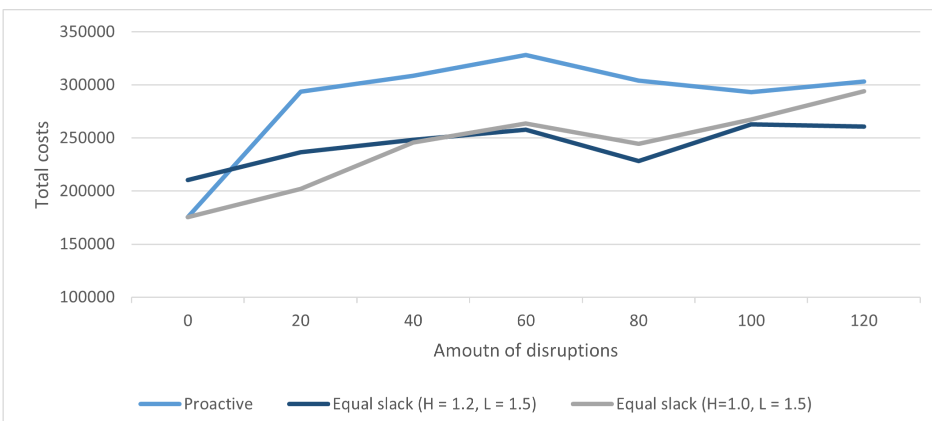


Figure 37: Total cost comparison for production projects 2 between different slack scenarios

Results scenario 6: Combination production project 1 and 2 Figure 38 presents the results for scenario 6, experiment 1. Following the trend of the above scenarios, the increase in lead time slack decreases the total costs. However, the effect of hour slack is more critical, as in scenario 5. This could be because of the larger number of production weeks taken up by scenarios 5 and 6, which do not all have to change when a lead time disruption happens. The cheapest option combines a 1.2 hour slack and 1.5 lead time slack factor.

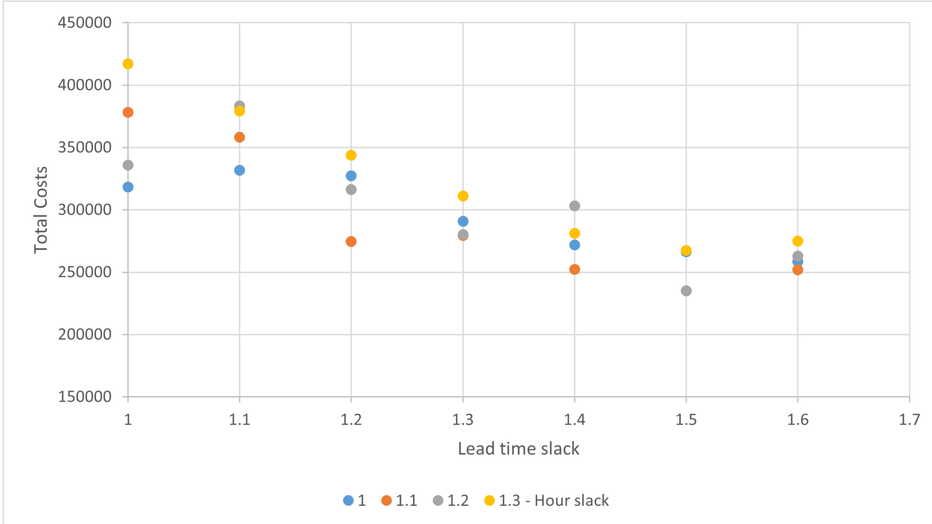


Figure 38: Indication total costs for a combination of production project 1 and 2, experiment 1, based on the amount of lead time slack and hour slack

The cheapest equal slack placement approach is compared with the proactive approach in Figure 39. Both methods use very similar costs, not distinguishing a clear better approach.

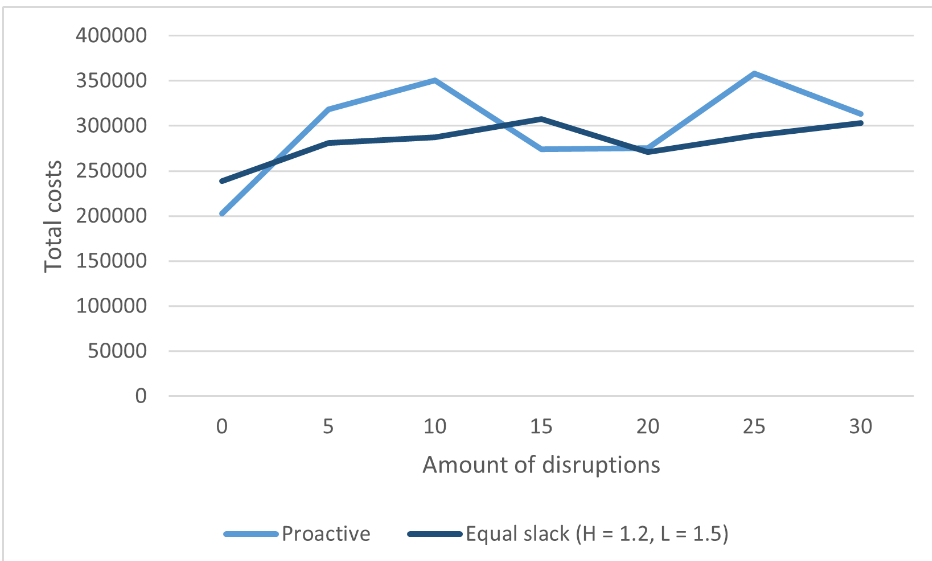


Figure 39: Total cost comparison for a combination of production projects 1 and 2 between different slack scenarios

Comparison between scenarios The results from all scenarios are compared to see if there are general trends and if new trends can be found. Several observations can be established across the above scenarios:

- The increase of lead time slack lowers the total costs. This trend is visible in scenario 2, where the slack is only tested against lead time disruptions. However, it is also visible in scenarios 3-6, where the increase in lead time slack lowers the total costs even when both types of disruptions occur.
- Hour slack is useful against hour disruptions, as shown in scenario 1, but does not work when a lot of lead time disruptions occur, as shown in scenarios 3-4. It appears to have a bit more effect in the larger production scenarios 5-6, but still, the hour slack increases in use when a higher lead time factor is used. Figure 32 also highlights this observation by showing an increase in unused hours when more

hour slack is added.

- Incorporation of slack at the end of a project is not useful when the disruptions happen upfront. This is because when a disruption within equal slack placement occurs, it can be solved within the same week and does not affect the other parts of the schedule. However, the entire schedule has to move when the disruption is solved with slack placement at the end. Therefore, when a disruption is known before the start of production, it is best solved with equally placed slack.
- Proactive placement of slack appears to be working worse or equally as well as good equal slack placement scenarios and has even better initialization costs. However, a disadvantage of proactive slack placement is that the slack is placed on a pre-determined number of disruptions that will occur. Therefore, knowledge of the number of disruptions is needed to place the right amount of slack. Furthermore, the proactive slack is determined by taking the average demand for slack for a number of disruptions that occur to the production plan. By taking the average demand over multiple runs, the shape of the original plan can become quite unlogical. Figure 40 illustrates the initially created project plan for proactive and equal slack placement for production project 1 for the case of 20 disruptions. The total costs for these disruptions are roughly the same; see Figure 28. The initial plan for proactively placing slack takes up many more weeks and does not have an equal-hour division. The equally placed slack scenario shows a shorter time frame and a more equal hour workload, which is more realistic for production at DIPP.
- The additional hours decrease when more hour slack is added, and the unused hour increases. In the case of increasing lead time slack, both the additional and unused hours decrease.
- Testing hour slack against hour disruptions shows that from a factor of 1.4 onwards, all hour disruptions are covered, and no additional hours are needed. Therefore, the peak of the hour disruptions, 1.3, seems to match the required slack. Similarly, testing lead time slack against only lead time disruptions shows that no additional hours are required from a factor of 1.8 onwards. Therefore, the needed lead time slack is moved towards the end of the lead time disruption range.
- To see if the total cost per project decreases when multiple of the same projects are combined, the costs of scenarios 3 and 4 are compared. However, the number of disruptions per project should be kept the same to make a fair comparison. This means the costs for 5 disruptions for a single instance are doubled and compared to those for 10 disruptions divided over two projects. Table 15 shows this cost comparison for several slack settings. Comparing the average costs per scenario, planning the production project twice does not affect the total costs much. In some cases, the total costs are slightly below, while in others, the costs are slightly higher. Therefore, it does not have cost benefits when two production projects, 1, are produced simultaneously.

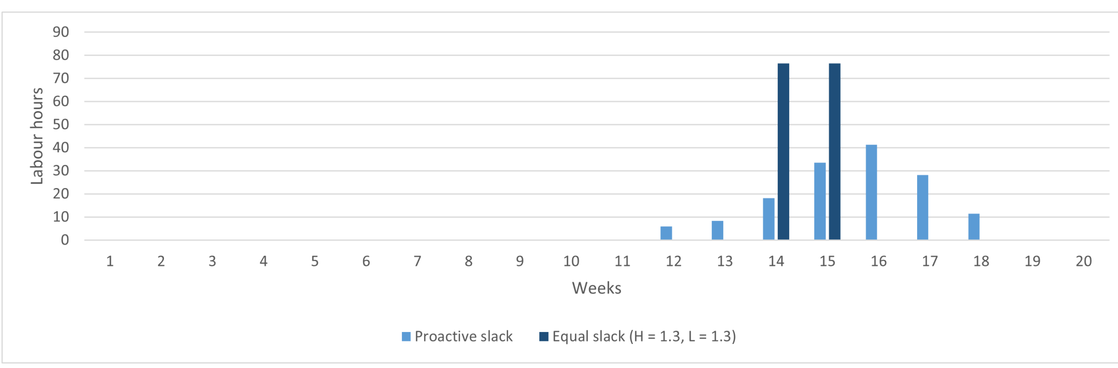


Figure 40: Comparison initially created production plan production project 1 between proactive slack for 20 disruptions and equal slack (H = 1.3, L = 1.3)

Disruptions	(H = 1.1, L = 1.1)		(H = 1.2, L = 1.2)		(H = 1.3, L = 1.3)		(H = 1.3, L = 1.6)	
	Scen 3	Scen 4	Scen 3	Scen 4	Scen 3	Scen 4	Scen 3	Scen 4
0	€23,600	€23,600	€25,960	€25,960	€28,320	€28,320	€30,680	€30,680
10	€34,426	€34,306	€34,447	€33,419	€36,724	€32,252	€33,119	€33,468
20	€46,056	€47,377	€45,813	€41,861	€40,773	€36,301	€31,731	€31,698
30	€53,077	€47,262	€53,465	€47,277	€36,423	€31,951	€39,266	€40,935
Average	€39,290	€38,136	€39,921	€37,129	€35,560	€32,206	€33,699	€34,195

Table 15: Total cost for production project based on the number of disruptions and parameter settings

Production plan advice project 1 and 2 Based on the above scenarios, DIPP's original project plans have been adapted to be more robust against future disruptions. For production project 1, Figure 41 shows the original plan compared to the best-performing scenarios and their costs. As producing two instances simultaneously did not turn out to be more cost-efficient, the best scenarios from scenario 3 are selected. An increased lead time factor shows better performance, looking at the average total costs over the disruptions, which amount to 0-30. The corresponding production plans are also shown, and while a longer lead time is cost-decreasing, the delivery time to the client increases. Therefore, this insight can be used to explain the trade-off to the client and agree on total costs and time.

	Average costs over all disruption amounts	Week 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Original planning	€ 23,339											59	59								
(H = 0, L = 1.1)	€ 22,033												59	59							
(H = 0, L = 1.2)	€ 20,493													59	59						
(H = 0, L = 1.3)	€ 18,542														59	59					
(H = 0, L = 1.4)	€ 16,288															59	59				
(H = 1.0, L = 1.5)	€ 15,725															65	65				
(H = 0, L = 1.6)	€ 15,058																59	59			

Figure 41: Advise production plan project 1 for decreasing costs, indicating needed hours per week

The original plan of production project 2 is also compared by taking average costs overall disruptions for multiple cheapest scenarios and their plan, both presented in Figure 42. Again, a trade-off has to be made regarding delivery time and total costs.

	Average costs over all disruption amounts	Week 1 to 25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Original planning	€ 333,478				251	251	251	251	251	251	251																
(H = 1.0, L = 1.1)	€ 302,028							251	251	251	251	251	251	251													
(H = 1.2, L = 1.2)	€ 280,716									301	301	301	301	301	301	301											
(H = 1.1, L = 1.3)	€ 264,508											276	276	276	276	276	276	276									
(H = 1.1, L = 1.4)	€ 235,258														276	276	276	276	276	276	276						
(H = 1.2, L = 1.5)	€ 179,443																301	301	301	301	301	301	301				
(H = 1.1, L = 1.6)	€ 190,902																		276	276	276	276	276	276	276		

Figure 42: Advise production plan project 2 for decreasing costs, indicating needed hours per week

5.4 Conclusions

This chapter studied the available data on past production projects and their disruptions. This data was used to validate the created models and gain better insight into the relation between created robustness through labour hour or material lead time slack and disruptions. The main conclusions are stated below.

- Based on past disruption data, disruptions to activity durations and start times are generated. The disruptions contain a multiplication factor for the original hour and lead time estimates. The labour hour disruptions are generated between a factor of 0.4 - 1.8, peaking at 1.3. The factor lies between 0.6 and 1.9 for the lead time disruptions, peaking at 1.3.

- Three experiments have been created to study various amounts and placements of slack to test against disruptions. The experiments evaluate the equal placement of slack over all production weeks, slack placement through proactive average approximation, and slack placement at the end of production planning. Each experiment is tested against six different scenarios. The first two scenarios assess the individual use of hour and lead time slack. The last four scenarios asses realistic production plans using production projects 1 and 2.
- Testing hour slack against hour disruptions shows that from a factor of 1.4 onwards, all hour disruptions are covered, and no additional hours are needed. Therefore, the peak of the hour disruptions, 1.3, seems to match the required slack. Similarly, testing lead time slack against only lead time disruptions shows that no additional hours are required from a factor of 1.8 onwards. Therefore, the needed lead time slack is moved towards the end of the lead time disruption range.
- Using a combination of lead time and hour slack on real production scenarios shows that the lead time slack keeps decreasing the costs when a higher factor is used. However, the hour slack increases the total costs at lower lead time factors as the additionally planned hours end up unused when the entire plan has to move because of lead time disruptions.
- Producing two instances of production project 1 close together does not affect the total costs per project when comparing the same disruption amount per project.
- Proactive placement of slack does not perform better than the best equal placement of slack scenarios. Additionally, proactive slack placement does result in unrealistic production plans upfront.
- The placement of end slack did not perform better than the equal slack placement scenario. This is because the experiments generate disruptions upfront before the plan has started, which leads the entire plan to be moved towards the slack placed at the end. This creates many deviations from the original plan, which is penalized in the rescheduling model.
- The best equal slack placement scenarios and their corresponding plans are created to indicate the trade-off between postponing production and the average costs for both production projects.

6 Implementation

This chapter discusses the implementation and maintenance of the model and tool. An interface for the models is created so that the project manager at DIPP can run the models without any Python knowledge. Next, the model's speed is improved, and maintenance is recommended. Therefore, the research question below is answered:

How can the model be implemented and maintained at DIPP?

6.1 Implementation

The models created by this thesis assist the project manager in creating production plans and helping with rescheduling during production. Below is a description of how a tool was implemented so that it can be used by the project manager. A separate maintenance manual will be provided to DIPP in addition to this chapter.

6.1.1 Interface and running time

A Graphical User interface (GUI) has been designed to use the created proactive and reactive model without accessing the code directly. The GUI can be seen in figure 43 and 44, screenshots of all screens have been added to the Appendix E. The GUI has several tabs and buttons that direct users to the model's functions. These include the deletion and adding of a project, creating a project plan, re-scheduling after a disruption, and the tool instructions are also added.

New added functions compared to the models are:

1. The planning can be downloaded to Excel to allow DIPP to adapt the plan to their liking.
2. An option to use a maximum amount of week hours in a week is added such that if there are capacity restrictions, these can be set.
3. An option to fixate projects when planning new ones is added and can be used if the planning of already running projects should not change.

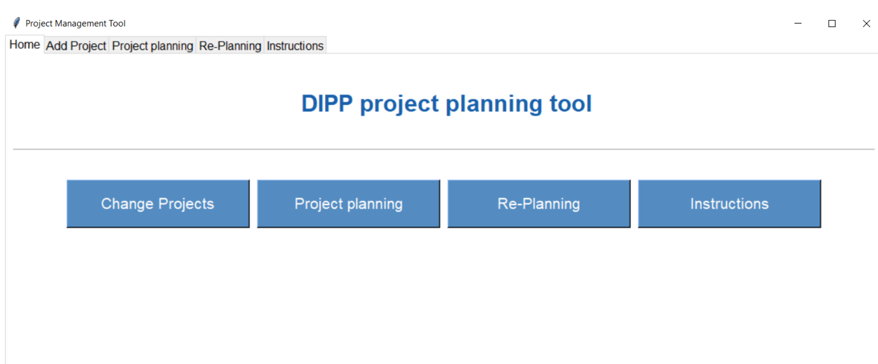


Figure 43: GUI start page

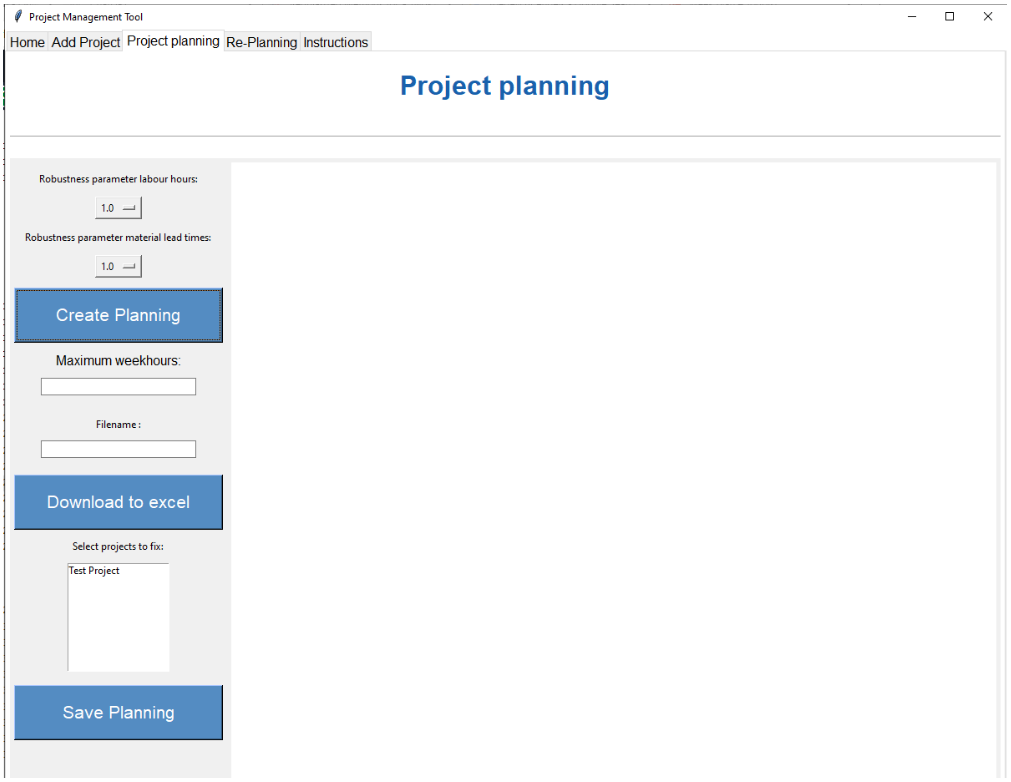


Figure 44: Project planning page GUI

The result of a created production planning can be seen in figure 45. The planning shows the labour hours needed per week per module to work according to the planning. The total hours needed per week are also shown in Excel.

	1100	1200	1300	1400	1500	1600	1700	1800	1900	Total Hours
24-31										
24-32										
24-33										
24-34										
24-35										
24-36										
24-37										
24-38										
24-39										
24-40										
24-41	24	24	24		8					80
24-42				20	12	16	16	12	4	80
24-43										

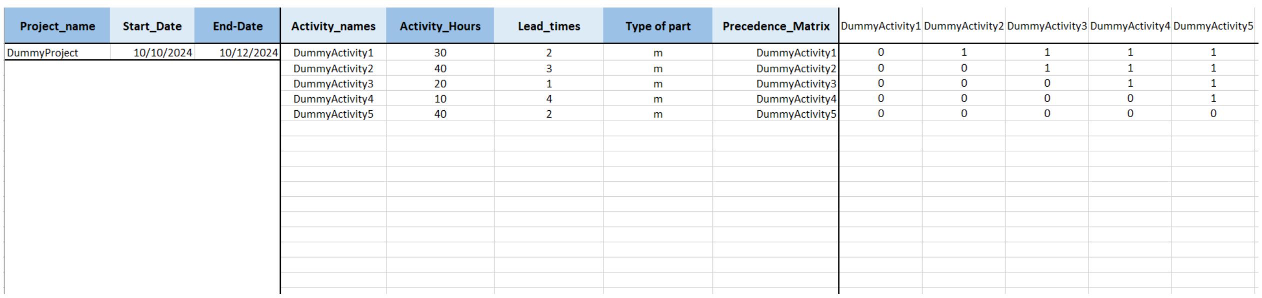
Figure 45: Example of production planning downloaded to Excel

To improve usability, the model's speed has been enhanced by adding several constraints that limit the calculation needed to get to an optimal model. For example, they restrict a production activity to only being planned after its lead time. Similarly, there can also be no planned labour hours in a week before the first material of a project has arrived. This is visible in Constraints (49) to (55).

$$x_{t,i} \leq 0, \quad \forall t \leq \text{leadtime}_i - 1, \forall i \in A \tag{49}$$
$$\text{bin}_{t,i} \leq 0, \quad \forall t \leq \text{leadtime}_i - 1, \forall i \in A \tag{50}$$
$$\text{first\_bin}_{t,i} \leq 0, \quad \forall t \leq \text{leadtime}_i - 1, \forall i \in A \tag{51}$$
$$\text{first\_ind}_i \geq \text{leadtime}_i - 1, \quad \forall i \in A \tag{52}$$
$$\text{weekhours}_t \leq 0, \quad \forall t \leq \min(\text{leadtime}) - 1 \tag{53}$$
$$\text{hourvariationweek}_t \leq 0, \quad \forall t \leq \min(\text{leadtime}) - 1 \tag{54}$$
$$\text{hourvariationcount}_t \leq 0, \quad \forall t \leq \min(\text{leadtime}) - 1 \tag{55}$$

6.1.2 Data input

An Excel template has been created to ensure easy data input into the model, which can be uploaded to the tool. This template allows for easy input of all required data on a production project, and the tool will read the data so that it can be used in the model. The template is visible in Figure 46 and filled with dummy data as an example.



Project_name	Start_Date	End-Date	Activity_names	Activity_Hours	Lead_times	Type of part	Precedence_Matrix	DummyActivity1	DummyActivity2	DummyActivity3	DummyActivity4	DummyActivity5
DummyProject	10/10/2024	10/12/2024	DummyActivity1	30	2	m	DummyActivity1	0	1	1	1	1
			DummyActivity2	40	3	m	DummyActivity2	0	0	1	1	1
			DummyActivity3	20	1	m	DummyActivity3	0	0	0	1	1
			DummyActivity4	10	4	m	DummyActivity4	0	0	0	0	1
			DummyActivity5	40	2	m	DummyActivity5	0	0	0	0	0

Figure 46: Template for production project input filled with dummy data

6.1.3 Installation

To get the tool working at DIPP, a change to the solver used must be made. This thesis used the solver Gurobi, for which the company provided a free educational license but which would cost DIPP money. As an alternative, the COIN-OR solver is implemented in the tool. This is an open-source solver and can be used for free. The solver does, however, limit the calculation speed of the models. Therefore, the recommendation to DIPP is made to use the tool with the COIN-OR solver at the beginning for small projects or to group activities for larger projects. If the tool is still helpful after one or more projects, an investment into a faster solver could be made. The manual explains how to implement other solvers.

6.2 Conclusions

The main points of this chapter are summarized below:

- A tool with a Graphical User Interface (GUI) has been created so DIPP can work with the models without accessing the Python code.
- To upload projects to the GUI an Excel template has been created, similarly the resulting production planning from the tool can also be downloaded to Excel.
- The Gurobi solver, used during the experiments, has been replaced with the COIN-OR solver. This free alternative can be used until DIPP decides if they want to invest in the Gurobi or another paid solver.

7 Conclusions and recommendations

This thesis has found solutions to improve DIPP's production planning, both through experiments based on current production projects and their disruption data and through a tool that can continue to assist DIPP with production planning in the future. This chapter will state the conclusions of this thesis and provide DIPP with recommendations. Lastly, directions for future research are suggested.

What recommendations and conclusions should be given to DIPP based on this research?

7.1 Conclusion

This research solves the core problem "How can DIPP improve their current production planning method to be more robust against disruptions such that the production projects stay within their set labour budget?". During the past production projects at DIPP, a lot of disruptions happened, which caused the labour hour budget to be increased by 45 percent. The analysis of the current situation at DIPP concludes that the current production planning method at DIPP does not assist the project manager in creating a robust plan against disruptions. Furthermore, the planning tool does not provide a good overview and requires much manual work. The studied production projects are divided into several activities that must be executed according to technological constraints. Furthermore, two types of disruptions are selected for this thesis: disruptions that affect the start time or the needed labour hours of a production activity.

The literature review provided insight into the categorization of the problem and provided knowledge on potential models to use. A proactive-reactive approach was selected to best deal with the high uncertainty and variability of disruptions during production at DIPP. As a basis for the proactive model implementation, the RCPSP was selected, combined with a makespan minimizing and resource levelling objective. An extension of the proactive model was made for the reactive model by including the minimization of overtime and disruptions into the objective. Robustness against disruptions was created using slack. Three alternatives are discussed for the placement of slack: equal distribution over all production weeks, slack placement based on proactive average approximation and slack placement at the end of the production plan. The models were implemented in Python and used to experiment with different amounts and placements of slack against disruptions. Six different scenarios were used to test the performance of the slack. These provide insight into the slack placement and effectiveness of the current production projects at DIPP and general insight into the slack placement and effectiveness against disruptions.

A Python tool has been built to allow the DIPP project manager to work with the models in the future. The tool creates a production plan based on information on production projects uploaded through Excel, allows for rescheduling after a disruption, and provides the option to download the created planning to Excel.

Based on this research, we conclude the following:

- The hour and lead time slack tested separately against their corresponding disruption type are effective. A slack factor equal to the average factor of hour disruptions, 1.3, is enough for the hour slack to be robust against the entire range of disruptions. For lead time slack, a slack factor at the end of the lead time range, 1.8, is needed to be robust against the entire range of lead time disruptions.
- The use of hour slack with a lead time slack factor on the lower side works counterproductive as the additional labour hours end up unused because of the many lead time disruptions. Therefore, hour slack should only be used when there are little lead time disruptions or when a high lead time slack factor is used.
- Equal slack placement overall production activities works better than proactively determining slack. This is because the proactively created planning does not produce a realistic production plan, and the total costs are not lower. Equal slack also performs better than slack when placed at the end of a production plan. This is because disruptions to the production plan are generated in created experiments before production starts. Therefore, equal slack can incorporate the disruptions in the plan without changing the planned activities in a week. In the case of end slack, activities need to be moved to further weeks, which our model penalises.
- For the current production projects, a trade-off is found between lower production costs and postponement of the production plan. The low costs mean the labour hour budget has not increased much,

representing the best-performing slack factor cases. The trade-off for both projects is visualized in Figure 47 and 48.

- The multi-project scenarios in this thesis did not indicate a decrease in average costs per project when the incorporated slack is shared.

	Average costs over all disruption amounts	Week																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Original planning	€ 23,339											59	59								
(H = 0, L = 1.1)	€ 22,033												59	59							
(H = 0, L = 1.2)	€ 20,493													59	59						
(H = 0, L = 1.3)	€ 18,542														59	59					
(H = 0, L = 1.4)	€ 16,288															59	59				
(H = 1.0, L = 1.5)	€ 15,725															65	65				
(H = 0, L = 1.6)	€ 15,058																59	59			

Figure 47: Trade-off between duration production and average costs for production project 1

	Average costs over all disruption amounts	Week																									
		1 to 25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Original planning	€ 333,478				251	251	251	251	251	251	251																
(H = 1.0, L = 1.1)	€ 302,028							251	251	251	251	251	251	251													
(H = 1.2, L = 1.2)	€ 280,716									301	301	301	301	301	301	301											
(H = 1.1, L = 1.3)	€ 264,508											276	276	276	276	276	276	276									
(H = 1.1, L = 1.4)	€ 235,258														276	276	276	276	276	276	276						
(H = 1.2, L = 1.5)	€ 179,443																301	301	301	301	301	301	301				
(H = 1.1, L = 1.6)	€ 190,902																		276	276	276	276	276	276	276		

Figure 48: Trade-off between duration production and average costs for production project 2

After this research, we conclude that DIPP has been provided with data insights and a tool to improve its current production planning method. Thus, we solved the selected core problem of this thesis. Within this thesis, we indirectly addressed the other mentioned core problems by accounting for variation in material lead times and the unpredictability of the labour hours estimations due to the lack of knowledge at DIPP. In conclusion, this research contributes partially to the action problem, the discrepancy between the norm and reality of staying within a set labour budget for a production project.

7.2 Recommendations

The insights gained from the experiments conducted by this thesis provide DIPP with the following recommendations:

1. Only incorporate a slack in labour hours when the plan is robust against lead time disruptions Incorporating hour slack when a lot of lead time disruptions occur only results in higher costs as the hours included through slack are unused when a lead time disruption postpones the production plan. Therefore labour hour slack should only be incorporated when there are no lead time disruptions or combined with a high lead time slack factor.

2. When hour slack is incorporated, spread it equally over all production weeks and use the created tool to use the additional hours optimally when a disruption occurs. When disruptions occur before the production plan starts, equal slack placement outperforms proactively placing slack based on the average slack demand against disruptions and by placing slack at the end. This is because equal slack placement keeps the project plan's timeline tight and limits disruptions to the initial plan. The created tool can incorporate equal slack into future production plans.

3. Use the created trade-off between total production costs and completion of production projects 1 and 2 to determine their future production plans The trade-off between total costs and the delivery time indicates that the further a project's start is postponed, sometimes combined with additional hours added, the further the project's total costs are decreased. The trade-off can be used to design a more robust production plan and potentially discuss a later delivery date with a client.

4. Collect data on the range and distribution of future disruptions to improve the knowledge of the required slack. The current data on disruptions used to perform the experiments is only based on the two production projects. To improve insight into the type, effect, and distribution of the disruptions, it is recommended that DIPP collects more disruption data from future production projects. This data can be used to identify common causes of disruptions and potentially tackle them. Furthermore, the ranges and distribution of the disruptions affect the slack factor needed to cover them.

7.3 Practical and scientific contribution

This thesis is performed at DIPP. The contribution to the company is the insight into the types and effects of disruptions that have increased the needed labour hours in past production projects. The relation between hour and lead time slack and their corresponding disruptions is uncovered. Based on these, general advice is given for future production projects and tailored to past production projects. Lastly, DIPP is provided with a tool to access the created production planning and rescheduling models in this thesis to simplify creating a robust production plan.

The scientific contribution of this thesis lies in the combination of uncertainty in labour hours and lead time uncertainty. This thesis highlights the significant effect of lead time uncertainty on production planning in the highly uncertain situation at DIPP. It shows that incorporating labour hour slack is counterproductive when many lead time disruptions happen. This thesis studies production planning with models based on the RCPSP. No literature study has considered this model and both kinds of uncertainty. Therefore, this combination and its insight contribute to the production planning and rescheduling literature.

7.4 Limitations and further research

This thesis has some limitations, resulting from the research scope and the complexity of the DIPP production planning context. These limitations can provide directions for future thesis topics.

- This thesis used a week-based production planning for labour hour optimization and used production activities to represent an action that needed to be taken and sub-parts of a product that needed to be built. The longest material lead time estimate is taken for each activity to create the production planning. As the lead time disruptions turned out to be highly important to the production plan, specifications between different categories of material or materials with a high risk of causing delay could also be considered.
- For the simulation of disruptions, this thesis chose to focus on two types: a change in the material lead time or a change in the labour hours needed to complete an activity. In future research, other disruptions, such as sick employees, can be considered.
- This thesis used three approaches to incorporate slack into production planning. Other techniques could be studied to compare their effect. Furthermore, this thesis tested the slack placements against disruptions generated at the start of the production plan. Testing against disruptions during the production plan could provide alternative insights.
- For the calculations of the total costs needed for an initial production plan and its re-scheduled plan after disruptions, the costs for a regular hour and overtime hour were used. To extend the options for additional hours, the hiring of external employees and the corresponding considerations can be taken into account.

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A Data projects

A.1 Detailed data production project 1

Startdate: 01/08/2024 Enddate: 25/10/2024

Activity_names	Activity_Hours	Lead_times	Type_of_part
1000	16	0	-
1100	10	4	m
1200	16	8	k
1300	16	8	k
1400	16	5	m
1500	16	5	m
1600	8	6	m
1700	8	6	m
1800	8	6	m
1900	4	7	k

Table 16: Activity Hours, Lead Times and Part Types of production project 1

Precedence_Matrix	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900
1000	0	0	0	0	0	0	0	0	0	0
1100	1	0	1	1	1	1	1	1	1	1
1200	1	0	0	0	1	1	1	1	1	1
1300	1	0	0	0	1	1	1	1	1	1
1400	1	0	0	0	0	0	1	1	1	1
1500	1	0	0	0	0	0	1	1	1	1
1600	1	0	0	0	0	0	0	0	1	1
1700	1	0	0	0	0	0	0	0	1	1
1800	1	0	0	0	0	0	0	0	0	1
1900	0	0	0	0	0	0	0	0	0	0

Table 17: Precedence Matrix with activity numbers of production project 1

A.2 Detailed data production project 2

Startdate: 14/02/2024 Enddate: 12/12/2024

Activity Number	Activity Hours	Lead Times	Type of Part
2000	32	21	k
2110	24	13	k
2120	16	20	m
2130	24	16	m
2160	120	11	k
2170	256	16	k
2210	24	15	m
2220	80	14	m
2230	32	14	m
2240	32	13	m
2250	32	16	m
2300	40	18	m
2310	20	17	m
2320	28	17	m
2330	28	18	m
2340	32	15	m
2350	28	18	m
2370	30	15	m
2411	80	14	m
2421	40	14	k
2431	16	13	m
2441	24	9	m
2460	8	15	k
2500	32	15	m
2600	48	18	m
2700	24	18	m
3110	56	21	m
3200	32	23	k
3210	56	22	m
3220	24	22	m
3230	32	21	m
3240	48	18	k
4000	88	16	m
5000	8	23	m
6210	32	21	m
7110	32	11	k
7120	32	11	k
7130	32	19	k
7140	32	13	k
7160	36	16	k
7180	32	4	k
7190	16	14	k
9000	16	9	m

Table 18: Activity Hours, Lead Times and Part Types of production project 2

Order	Activity
1	2000
2	5000
2	6210
3	2600
4	7160
4	7180
5	2460
6	2411
6	2421
6	2431
6	2441
7	2120
8	7130
9	2700
10	2500
11	2300
12	2350
12	2370
13	2310
13	2320
13	2330
13	2340
14	4000
15	2170
15	2210
15	2220
15	2230
15	2240
15	2250
16	2110
16	2130
16	2160
17	7110
17	7120
17	7140
20	3200
21	3110
21	3210
21	3220
21	3230
21	3240
21	7190
21	9000

Table 19: Order of activities for production project 2, as replacement of visualizing the precedence matrix. If a number is higher than another, it must be executed first.

B Validation cases re-scheduling

B.0.1 Validation of the proactive production planning model

After putting all the data into the proactive planning tool the plan in Figure 49 is generated. The planning is manually validated through the following points:

- **Precedence relations**: the activities are planned in the correct order.
- **Deadline**: the deadline is met.
- **Completeness**: all activities are planned in completely.
- **Hours**: the hours planned match the needed hours.
- **Lead time**: the set leadtime is met.
- **Objective**: the project makespan is compact, and the hour variation is minimal.

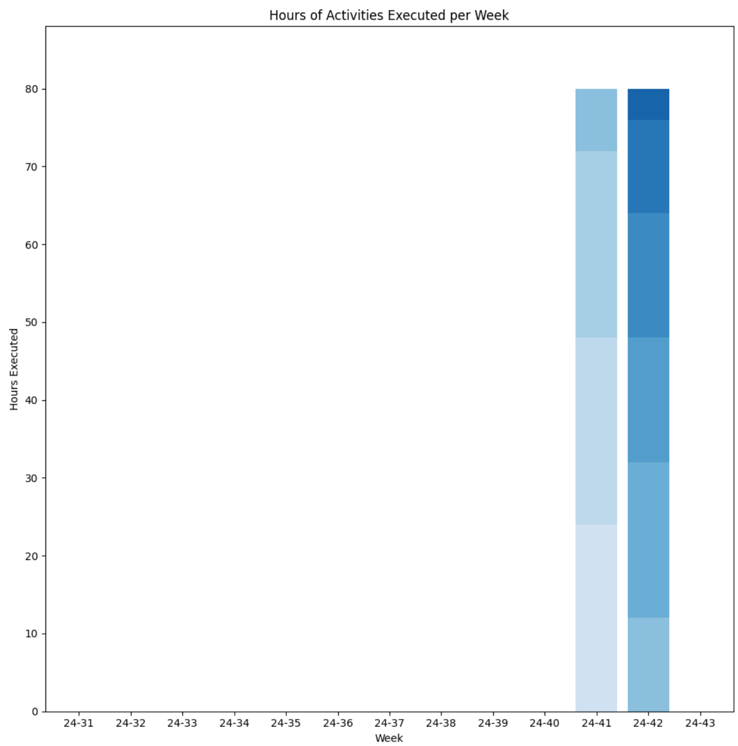

Figure 49: Planning created by proactive model for production project 1

B.0.2 Validation the reactive re-scheduling model

Random disruptions have been tested to validate the rescheduling model, and their effect on the model has been verified. Some examples are shown below.

Disruptions to model	Effect on the model	Correct?
Hour change first module from 24h to 40h	More hours (16) planned in evenly over the weeks	Yes
Hour change sixth module from 16h to 40h	More hours (24) planned in evenly over the weeks	Yes
Change in leadtime first module from 8 to 10 weeks	Start production first module, and al following(by precedence relations) moved to the next week	Yes

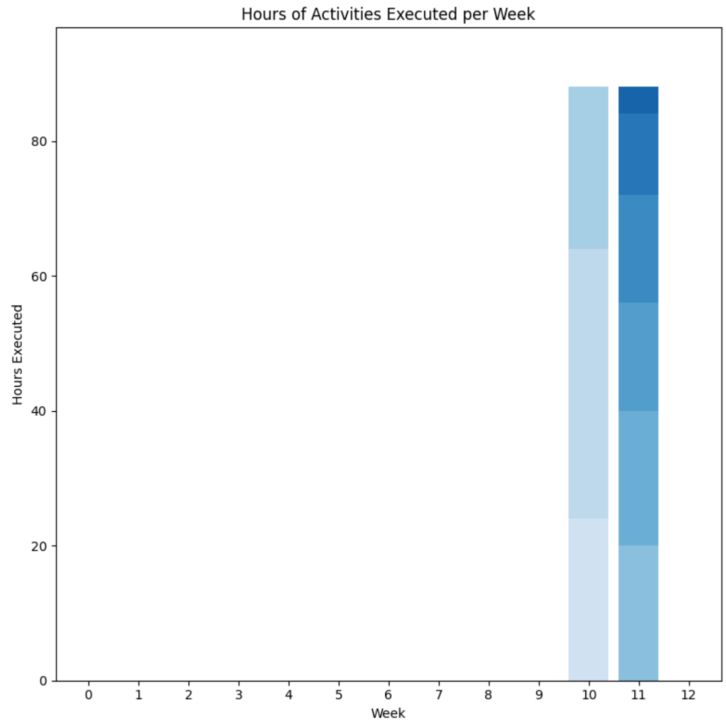

Figure 50: New planning after module 1 needs 40 hours instead of 24

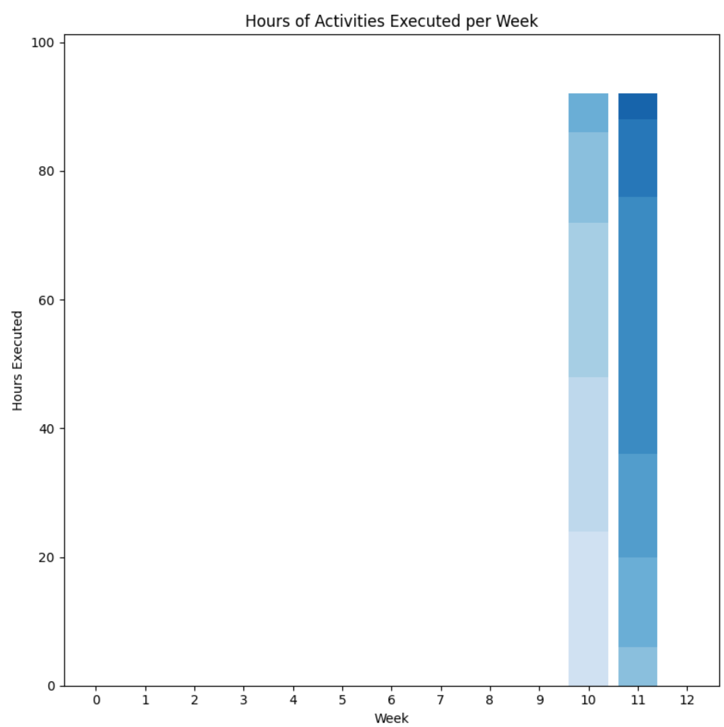

Figure 51: New planning after module 6 needs 40 hours instead of 16

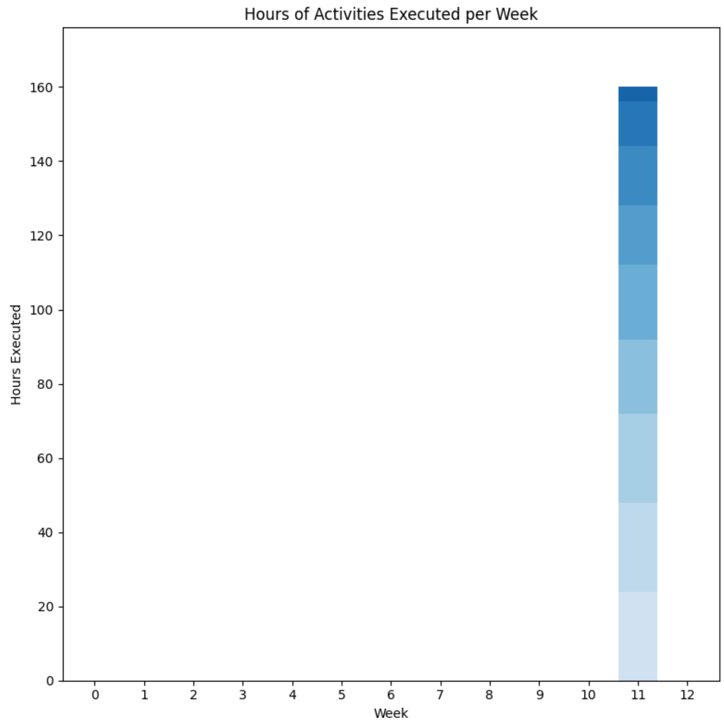

Figure 52: New planning after the leadtime of module 1 is changed to 11 weeks.

C Start scenarios experiments

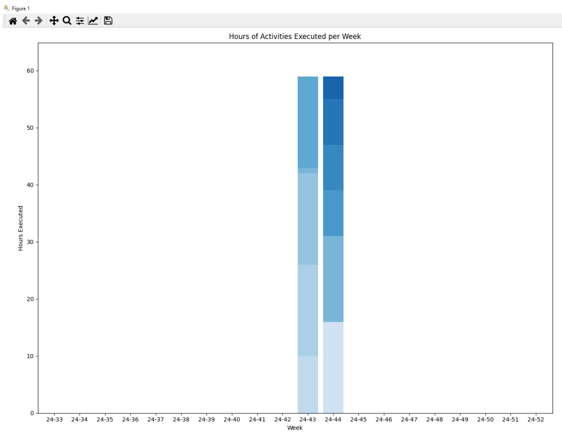

Figure 53: Start scenario 1

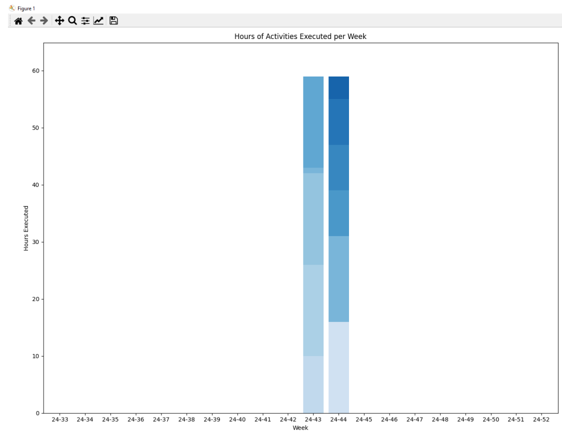

Figure 54: Start scenario 2

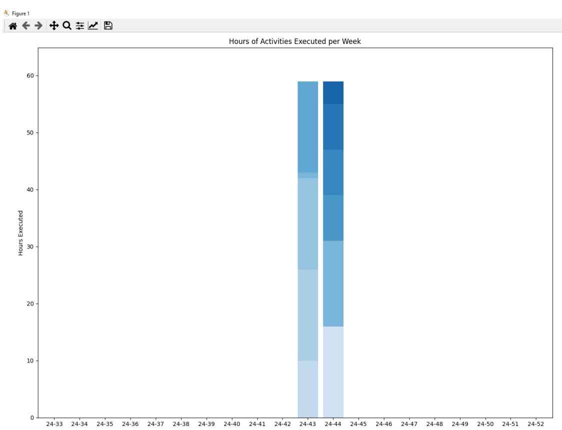

Figure 55: Start scenario 3

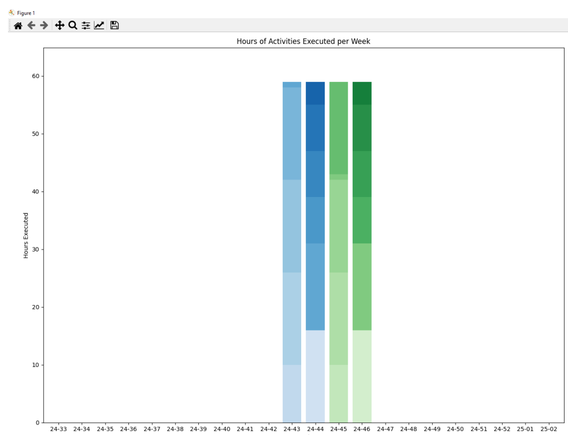

Figure 56: Start scenario 4

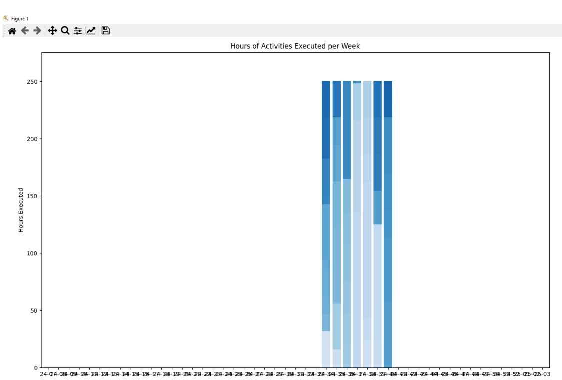

Figure 57: Start scenario 5

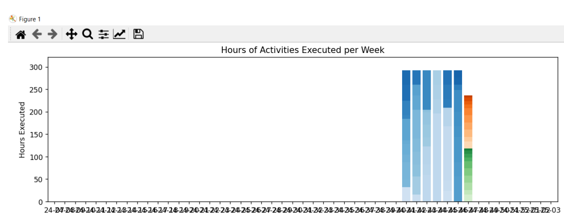

Figure 58: Start scenario 6

D Detailled set-up Experiments

Approach experiment 1: Equally placed slack

1. Input from the to-be planned projects is given to the proactive model and the values for both robustness parameters. These parameters ensure the equal placement of slack
2. The proactive model is run and produces an output with the needed labour hours per week as well as the fractions of the production activities that are planned for that week.
3. Y disruptions are produced and given to the re-scheduling model and the original planning.
4. The reactive model is run and produces an output with the needed labour hours per week, including possible overtime, as well as the fractions of the production activities that are planned for that week.

Approach experiment 2: Average approximation slack

1. Input from the to-be planned projects is given to the proactive model with both robustness parameter values set to 1, meaning no proactive robustness through that way.
2. The proactive model is run once to establish a baseline for production planning.
3. X times Y disruptions are generated, and the input for the proactive model, thus the L_i and H_i parameters are adapted accordingly, just like in the re-scheduling model.
4. The proactive model runs X times, each with a different Y amount of disruptions and produces X outputs with the needed labour hours per week and the fractions of the planned production activities. The labour hours needed per week are averaged over all X times, providing a slack placement over the weeks. As planned fractions, the baseline fractions are put in from step 2.
5. The reactive model is run for Y disruptions as well and produces an output with the needed labour hours per week, including possible overtime, as well as the fractions of the production activities that are planned for that week.

Approach experiment 3: Slack at the end

1. Input from the to-be planned projects is given to the proactive model with both robustness parameter values set to 1, meaning no proactive robustness through that way.
2. The proactive model is run and produces an output with the needed labour hours per week as well as the fractions of the production activities that are planned for that week.
3. Z percentage of slack is taken over the total amount of labour hours and put after the last production week in the planning, or if not possible, on top of the last production week. The weekly hours, including the slack, are given as input to the reactive model.
4. The reactive model is run with Y disruptions and produces an output with the needed labour hours per week, including possible overtime, as well as the fractions of the production activities that are planned for that week.

E Screenshots Demcon Tool

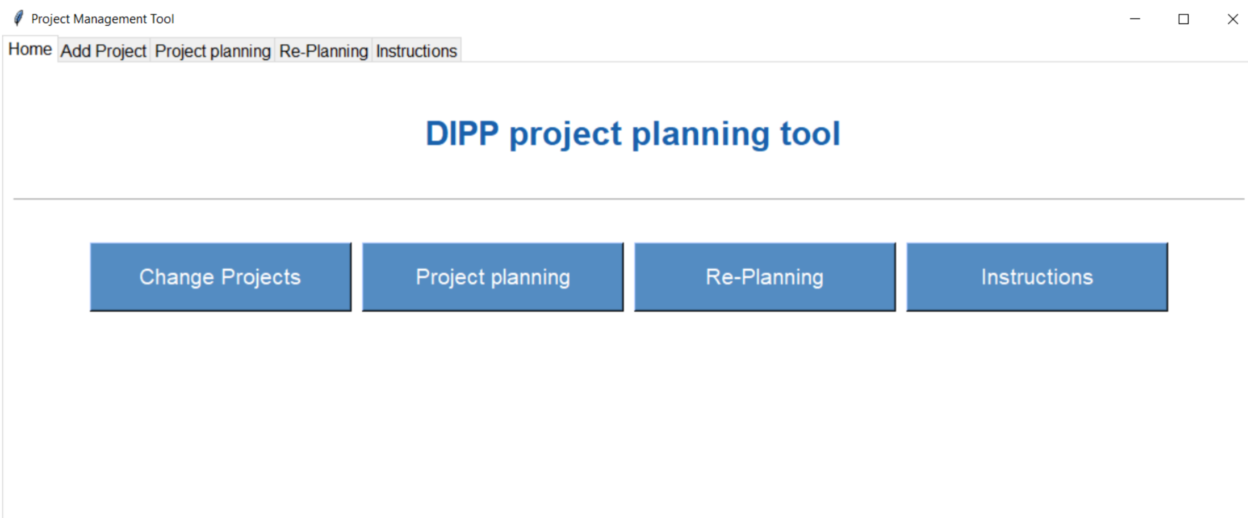

Figure 59: Start screen Demcon Tool

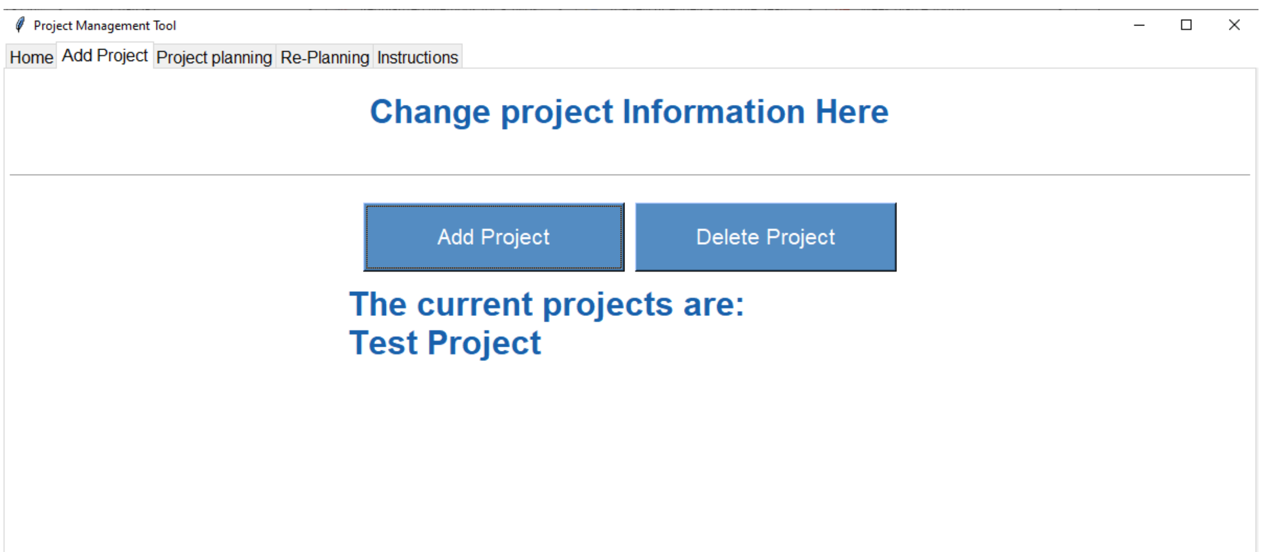

Figure 60: Screen to change the uploaded projects

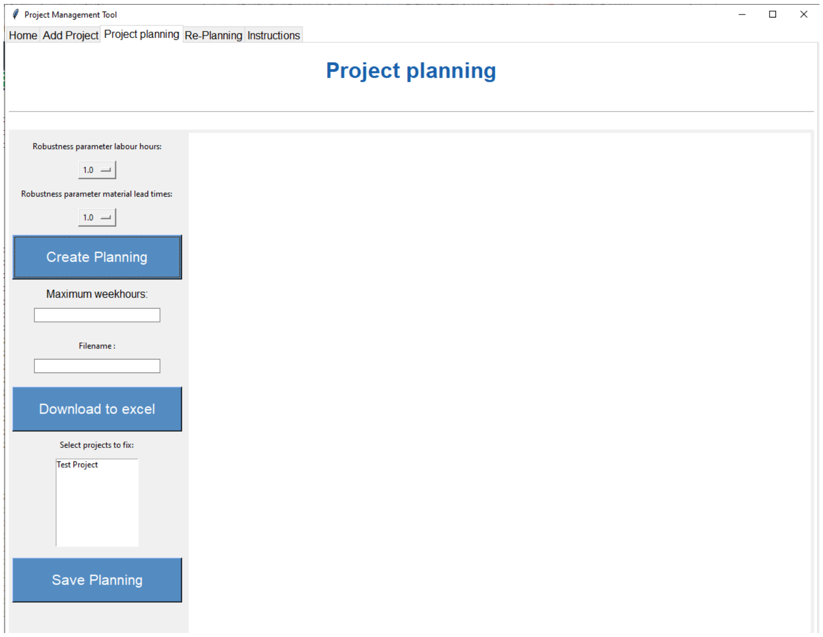

Figure 61: Screen to create a project plan with slack and boundary setting options.

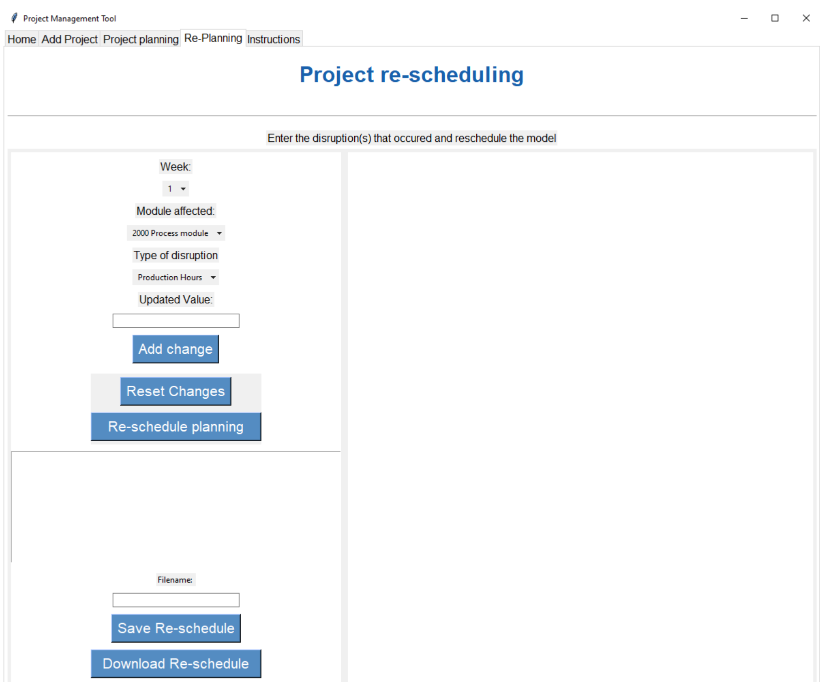

Figure 62: Screen to reschedule a project plan with specified disruptions.

F Objective weight selection

The weights in the objectives for both the proactive and reactive models can be adapted to change the output of the production plans. As the value of the objectives depends on the input and thus also on the deadline, different weights are needed to create the original DIPP planning compared to the plan tested in the experiments. The makespan in the experiments is kept the same as the original plan so a fair cost comparison can be made.

The weights for a production project should result in a production plan that resembles the original plan. Thus, the makespan of the production project 1 should be 2 weeks, and the weeks should be planned in weeks 11 and 12. The makespan calculated in Constraint 24 corresponds to a value of 13 (first activity in week 11 + makespan of 2). This value was used to select appropriate weights. Table 20 shows all the weights corresponding to this makespan.

w_Hc	w_Msp	w_Hv	Obj Value
0 - 1.0	0.5	0.1	0.054248366
0 - 1.0	0.6	0.1	0.056209150
0 - 1.0	0.7	0.1	0.058169935
0 - 1.0	0.8	0.1	0.060130719
0 - 1.0	0.9	0.1	0.062091503
0 - 1.0	1	0.1	0.064052288
0 - 1.0 except 0.6	1	0.2	0.108496732

Table 20: Summary of w_Hc, w_Msp, w_Hv, and corresponding Obj values for plan production project 1 identical to the approach of DIPP

A similar approach was used for all other weights; the results are shown in Table 21.

Obj Value	w_Hc	w_Msp	w_Hv	w_Am	w_to	w_td
Original proj 1	0.1	0.5	0.1	0.1	1	1
Original proj 2	0.1	0.2	0.1	0.1	1	1
Experiments proj 1	0.1	1.4	0.1	0.1	1	1
Experiments proj 2	0.1	0.3	0.1	0.1	1	1

Table 21: Summary weights used in objective for original plans and experiments for production projects 1 and 2. The last three weights are only used in the reactive model