Improving the planning of engineers and programmers at Romias

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Management summary

Introduction

This research project is conducted at Romias, a company that is specialized in the automation of production processes in the metalworking industry. Romias faces some challenges with the planning of staff (engineers and programmers):

- There is a gap between estimated and actual hours of project effort;
- Disturbing activities are performed immediately after occurrence, causing delay of the planning and/or overtime;
- Delayed delivery of projects.

Goals

In this research, we identify and assess improvements for the planning of engineers and programmers. We formulated the following research goal:

"Get more insight in the current planning of staff at Romias and to find a method to make the planning more efficient to prevent overtime and delays."

In this statement, we formulate overtime as the extra time that staff works outside the standard working hours and delays as the extra time that is needed to complete certain tasks. To reach the research goal, we make use of the following of the following research question:

"How can Romias improve the planning of engineers and programmers in such a way that they are able to perform all their tasks within the planned time?"

Approach

We analyzed the current situation at Romias and conducted a literature study to find an answer to the research question. For the analysis of the current situation at Romias, we interviewed staff members and management. We also made use of the current planning, project offers and hour registrations to compare estimated and actual project effort. In the literature study, we compared the planning of engineers and programmers to the planning of operating rooms in hospitals, since these planning processes have some characteristics and practices that can be useful in the planning of staff at Romias.

With the gained knowledge, we identified potential improvements of the planning at Romias, which we tested with a simulation model. We therefore simulated the engineering parts of two different Engineer-To-Order projects. We compared the results of interventions to the current planning process to determine which interventions do indeed improve the performance of the planning of staff.

Results

In the standard scenario, the average throughput time of project A is 119 days. However, 49% of the projects will be delivered after the agreed deadline. We simulated different scenarios in which we changed some input parameters of the model:

- Competence levels of engineers
- Dedicated engineer for the disturbing activities
- Work in overtime
- Priorities of disturbing activities

We concluded that it is not beneficial to have an engineer that only performs disturbing activities. All other interventions do improve the planning in terms of throughput time and lateness of projects.

1. The first intervention showed that it is beneficial to let one or two engineers focus on the project activities, while the other(s) also perform disturbing activities. It is not efficient to enable all engineers to perform both project and disturbing activities.
2. Work in overtime reduces the throughput times of projects in terms of days. It can be used to work on projects that are expected to be delivered too late. When engineers work 8 hours per week in overtime, the probability that a project is delivered reduces from 49% to 2%.
3. Prioritizing disturbing activities leads to a decrease of switching time between activities and therefore to a reduction of throughput times. When only 50% of all the disturbing activities can wait until the next day / after the lunch break.

Conclusion

The most promising intervention is the prioritizing of disturbing activities. Romias does not make a distinction between disturbing activities at the moment, while it can save valuable switching time. We recommend further research to determine the nature of disturbing activities and their priority. We also recommend to make one of the engineers responsible for the disturbing activities. This engineer can work on project activities in the rest of his/her time. The same holds for the programmers. We recommend to make it easier for engineers and programmers to register their activities. This makes it easier to estimate the duration of activities of future projects.

Preface

Amersfoort, January 2018

This report is the result of my graduation project to obtain my master's degree Industrial Engineering & Management. I would like to thank Martijn for giving me the opportunity to be part of Romias during this period. Thanks to you, my period at Romias was more than just a graduation project. I liked the trips to (potential) customers and the way you involved me in managing this young, dynamic company.

I also would like to thank my supervisors at the University of Twente. Sandor, you helped me during the whole process of setting up the research until its completion. I appreciated our meetings, it always gave me new inspiration and energy to continue the project. Matthieu, thank you for helping me out with the simulation study and giving me new insights and suggestions.

I would like to thank Maria Tine for her encouragement during the project, it really helped to stay positive. At last, I thank all my friends and family for the support over the years. Without you, I would never be a MSc!

Aldert Dijksterhuis

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1 Introduction

The industrial focus shifts more and more to customer specific products. Customers demand a very high degree of variety, combined with low (design) costs and lead times. Especially for companies that engineer products to order, this makes it hard to organize the internal processes. To fulfil the demands of the customers, these companies often face longer lead times and higher design costs (Dekkers, 2006). Companies should meet both the demand of high product flexibility and lower lead times / costs to survive. A key factor in the performance is the integration of sales, engineering and manufacturing (Furukawa, 1993).

Romias has to cope with the conflicting requirements of increasing variety and reducing the costs and lead times of design, engineering and assembling of customer specific robot systems.

This chapter provides information on Romias and the products that they make. It also describes the research goal and the research questions. Section 1.1 describes the company. Section 1.2 provides more context of the problem that we will analyze in this study. Section 1.3 outlines the research goal and the scope of the research. It also elaborates on the research questions and the methodology used during this research.

1.1 Romias

Romias is a ten-year-old company from Enter, that is specialized in the automation of production processes that improve the efficiency of firms in the metalworking and plastic processing. Romias strives to eliminate the human factor in reliability of solutions and wants to improve flexible processes with high mix and low volumes due to small changeover times. This is done using industrial robot systems. Romias takes care of the entire process of advice, engineering, assembling, implementation, training of workforce and support in the startup phase. So, it provides customer-specific solutions. Since a few years, Romias also delivers a standard robot system.

Romias had a turnover of €1.1 million in 2016, has 15 employees and aims to double its turnover 2017. In 2017, the firm starts for the first time producing a robot system in series for one specific customer and starts to import and sell AGV's from Clearpath (Canada) as being their first trading partner in Europe.

1.1.1 Company structure

Romias is a relatively small firm with a flat organigram. Figure 1.1 shows the organigram.

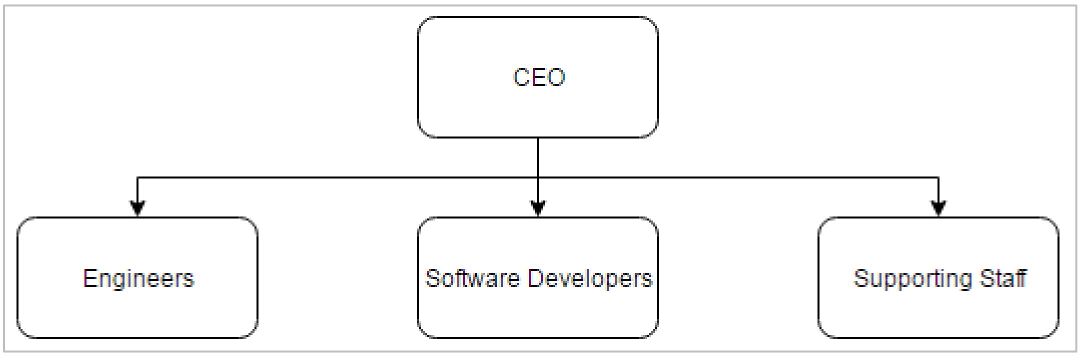

Figure 1.1 Organigram Romias

The engineers design the robot systems, make graphical representations and deal with safety regulations. The software developers are responsible for the functionality of the system. They write software for the customers, which they use to operate the system. The supporting staff takes care for administrative work and billing.

Romias is part of a holding with two other Dutch companies and has one international sales partner in Germany. (Figure 1.2)

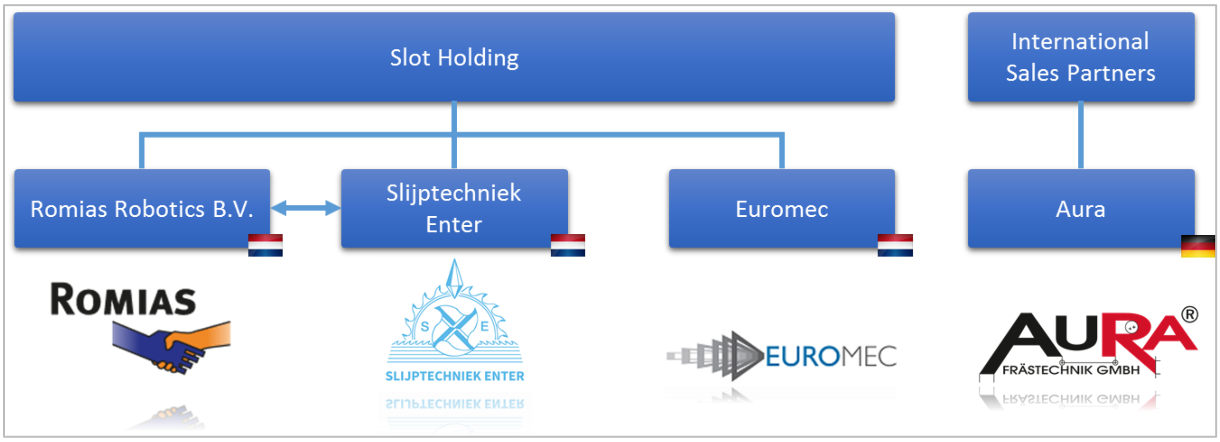

Figure 1.2 Holding Romias

1.2 Context of the problem

At the moment, a lot of projects are finished after de agreed delivery date, which leads to unsatisfied customers. Figure 1.3 shows support for the delay of projects. The estimated hours that are required to complete these projects were far too low, resulting in a lot of (unexpected) extra work/costs.

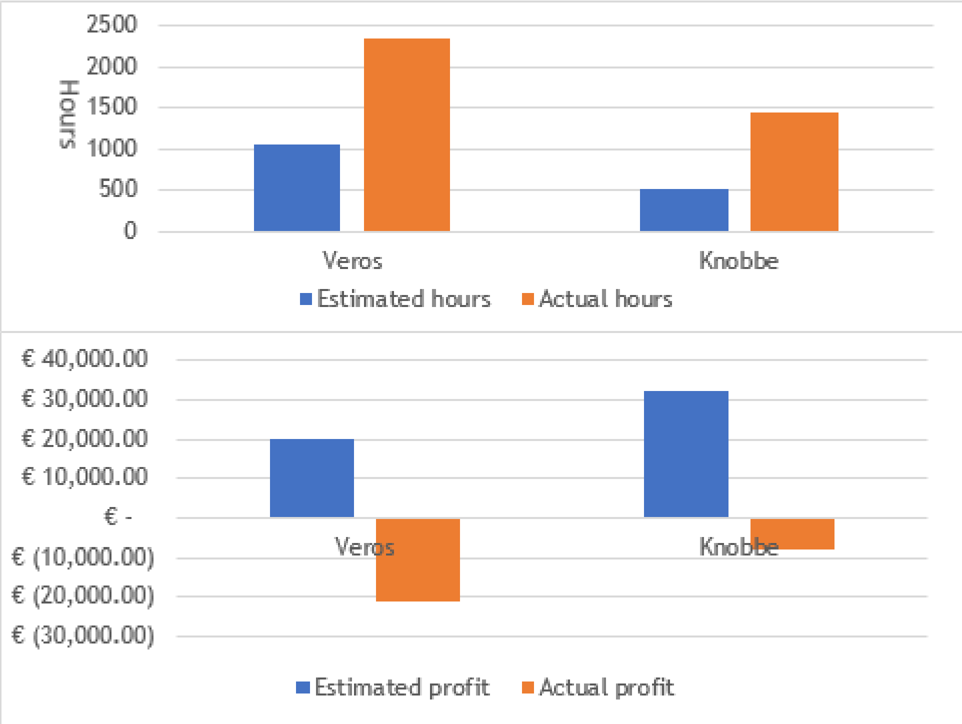

Figure 1.3 Comparison of estimated and actual hours & profits of projects

We distinguish two different problems:

1. There is a gap between estimated and actual hours
2. Romias delivers its projects after the agreed deadline

These problems are related to each other when a longer duration of projects leads to not meeting the deadline.
However, the first problem does not always result in the second. A project can have a longer duration than estimated, but still be delivered before the deadline when it started in time.

Problem 1 costs Romias a lot of money, since unforeseen hours are made where the customer doesn't pay for. The agreed price is based on the estimated number of hours.

Problem 2 does not directly lead to extra costs for Romias (we assume that no agreements are made about a late delivery). Problem 2 is not always the result of Problem 1. It can be that Problem 2 is caused by unplanned activities that are deterring staff from working on the planned activities / projects. We refer to these activities as disturbing activities or contingencies.

The gap between estimated and actual required hours is directly related to the planning and scheduling of engineers and programmers, since their planning is based on the estimated hours. We divide the activities that are performed by engineers and programmers into three different (project) types:

- Serial production
    - Standard procedures
    - Easy to estimate activity durations (low variability)

- Prototype building
    - Customized projects
    - Requires a lot of new engineering and programming
    - Hard to estimate durations (high variability)
- Disturbing activities (breakdowns, failures at customer)
    - Unplanned
    - Frequency of occurrence and durations are both hard to estimate
    - Affects the planning of project activities

When we refer to projects, we can refer to both serial production and prototype building. A more detailed explanation of these activity types can be found in Appendix A.

In the current situation, the planning of engineers and programmers consists for (almost) 100% of activities in the categories serial production and prototype building. However, due to disturbing activities and variable (longer) duration of planned activities the planning is delayed:

1. The disturbing activities are performed immediately after occurrence;
2. Disturbing activities are performed in the time that is planned for serial production and prototype building;
3. The activities in the categories serial production and prototype building cannot be performed in the planned time;
4. The remaining work has to be done at the end or after the working day (overtime) or next days, after all resulting in delayed delivery of the project;
5. The planned activities can have a longer duration than expected, resulting in even more delay.

The variable duration leads to the probability that the actual required hours to perform activities are greater than the hours that were estimated before. This directly results to Problem 1.

Disturbing activities lead to extra/unforeseen work for the engineers and programmers. Their planning does not incorporate these activities. Thus, when they perform disturbing activities, this means that the can't use that time for planned activities in serial production or prototype building. Disturbing activities lead to overtime, since engineers and programmers must perform their planned activities on a later moment. This can (not necessarily) result in Problem 2. Disturbing activities do not directly lead to extra hours that engineers and programmers need to perform their project activities. (Problem 1)
Table 1.1 summarizes the relations between these problems and causes. Figure 1.4 shows the causal analysis of the planning related problems at Romias.

Causes	Problems: Gap between estimated and actual duration	Problems: Projects delivered too late
Variability in activity duration	• Planning based on estimated hours. When the variability in the activity duration is high, this increases the probability that the actual duration is much higher than estimated. • Project costs more hours and money than expected. • Planning delays, since it is based on estimated hours.	• When the engineering and programming activities of projects take so much longer than expected, the probability that the deadline of a project can't be met arises.
Disturbing activities	• No direct relationship. • Disturbing activities can affect the productivity / work efficiency. • Switching times.	• Disturbing activities directly affect the planning of engineers and programmers, since they are not part of the planning. • Planning therefore delays. • Too much delay results in not meeting deadline of the project.

Table 1.1 Relations between problems and causes

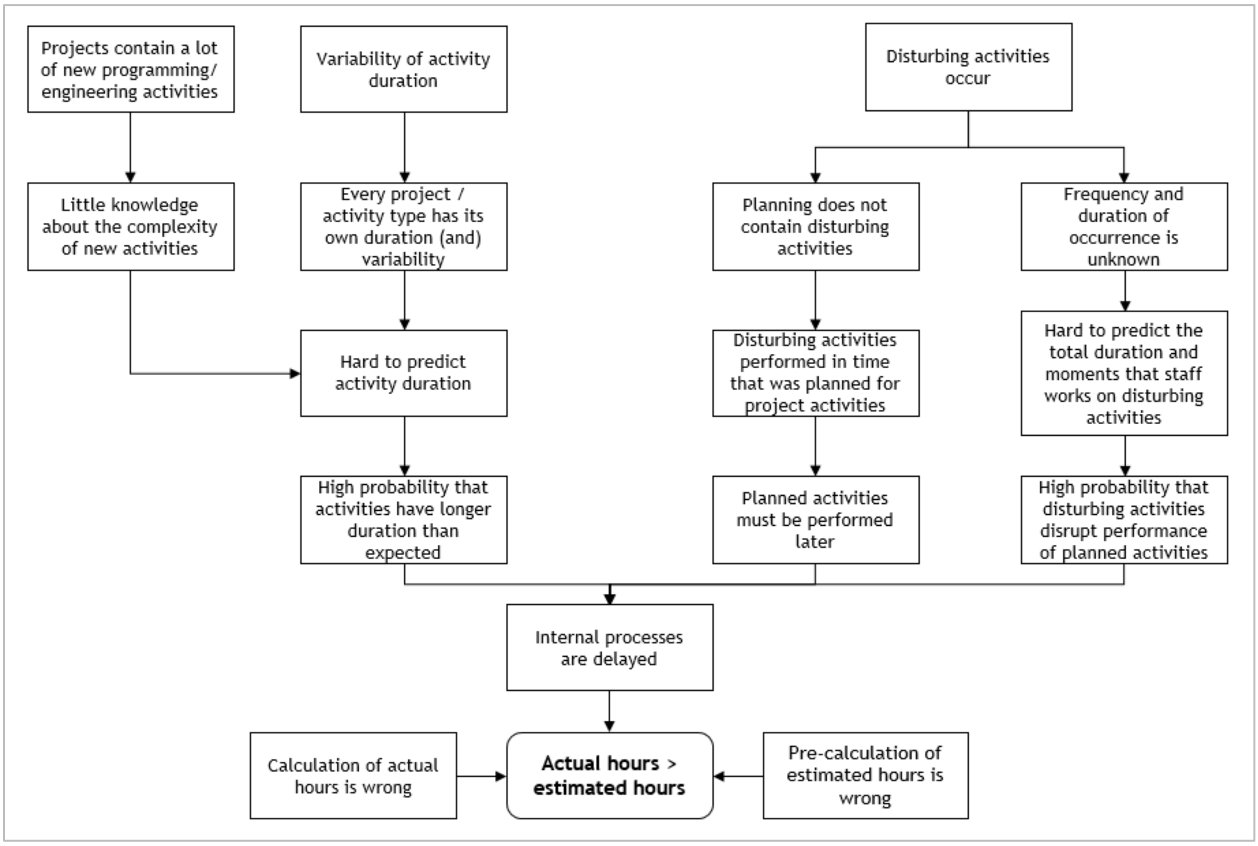

Figure 1.4 Root cause analysis of planning problems at Romias

The gap between estimated and actual hours of project activities is (possibly) caused by three reasons:

- The pre-calculation / offer calculation with estimated hours is wrong. A wrong risk factor is applied to the activities, most of the time it is too optimistic. Based on these data, an unrealistic deadline is determined.
- Internal processes are delayed.
- Calculation of actual hours is wrong. When a project is finished, it can be hard to assign the right amount of time to project activities. It is possible that a part of the assigned time is not spend on the project at all, but to disturbing activities for example.

In consultation with the management of Romias we decided to focus on the delay of internal processes (related to the planning of engineers and programmers) and to ignore the pre-calculation and final calculation of hours spend on project activities.

The internal processes at Romias are in the end delayed by two factors:

- Variability in the duration of planned project activities
- Occurrence of disturbing activities

The planning of engineers and programmers is very unstable due to these two reasons. The planning contains no capacity for them to perform/solve disturbing activities. Every disturbing activity will immediately cause a delay in the planning.

The variability of activity durations also causes problems for the planning. The planning delays when variability causes longer duration, since possible variation is in not incorporated in the planning. Besides that, engineers and programmers work longer on these activities than planned. This costs money, because the project price is based on the estimated hours and is determined on forehand.

1.3 Research objectives and questions

The goal of this research is to get more insight in the current planning of <u>staff</u> at Romias and to find a method to make the planning more <u>efficient</u> to prevent <u>overtime</u> and <u>delays</u>. We will use a research question and multiple sub-questions to achieve the goal.

<u>Staff:</u> In this research, we will refer to staff as the engineers and the programmers. Their work is directly related to projects.

<u>Efficient:</u> Coelli, Rao, O'Donnell, & Battese (2005) describe efficiency as the maximum output y that can be reached with input x. The planning of staff at Romias is effient when the planning corresponds to the actual time allocation.

<u>Overtime:</u> The time that staff works outside the standard working hours.

Delay: Delay is related to the planning of a project or staff member. A project is delayed when it is not delivered on or before the agreed deadline. A planning is delayed when planned activities cannot be performed in the calculated time.

1.3.1 Research scope

To define the research scope, we use the framework for planning and control that was originally used for healthcare processes (Hans, van Houdenhove, & Hulshof, A framework for Healthcare Planning, 2011). This framework summarizes all the planning and control activities of a company by using two different axes:

- Managerial areas
  Since most managers tend to focus on just one managerial area, this framework aims for integration of all the different planning functions: Technological planning, resource capacity planning, materials planning and financial planning. The difference between resource capacity planning and materials planning is that materials planning is about consumable resources and that resource capacity planning includes all the planning of renewable resources.
- Hierarchical decomposition
  We discern a strategic, tactical and operational (offline & online) level. At a strategic level, both supply and demand are unknown. Decisions at strategic level are dealing with a company's mission. Daily planning and control is done at the operational level. We make a distinction between the planning and control in advance (offline) and reactive decisions (online). Between the strategic and operational level is the tactical level. At this level, we have more information about supply and demand. For example, we know how large our facilities are and which machines we want to use. (Hans, van Houdenhove, & Hulshof, A framework for Healthcare Planning, 2011)

We modified this framework for the situation at Romias. Figure 1.5 shows the result.

	Technological Planning	Resource Capacity Planning	Materials Planning	Financial Planning
Strategic	Research development of robot systems, software and regulations	Capacity dimensioning, workforce planning	Supply chain and warehouse design	Investment plans, contracting with customers
Tactical	Specification selection, engineering / software requirements	Layout design selection, tool selection, staffing, long term project planning	Supplier selection, tendering	Budget and cost allocation
Offline Operational	Engineering and software development	Planning and scheduling of engineers and programmers	Materials purchasing, determine order sizes	Billing, cash flow analysis
Online Operational	Solving failures at customer	Monitoring, contingencies / disturbing activities	Rush ordering, inventory replenishing	Billing complications and changes

hierarchical decomposition

managerial areas

Figure 1.5 Framework Planning & Control

Romias is a multi-project organization. It runs multiple projects at the same time, which sometimes need the same resources (machines, tooling and staff) at the same time. The potential conflicts are in the area of Resource Capacity Planning. (Wullink, Hans, & Leus, A hierarchical approach to multi-project planning under uncertainty, 2004) We will therefore focus mainly on Resource Capacity Planning in the remainder of this research. However, since a decision always influences other managerial areas and hierarchical levels, this is not a strict limitation of the research scope.

For this research, we make some assumptions:

- We cannot influence the delivery times of suppliers;
- The costs of the robot and other materials are fixed;
- The deadline for a project is determined in such a way that Romias is able to meet it with the resources (staff, floor space, equipment) that are available at the moment that an agreement about the delivery date is made;
- We only take into account the internal processes at Romias.

1.3.2 Research question and methodology

The research question for this study is:

How can Romias improve the planning of engineers and programmers in such a way that they are able to perform all their tasks within the planned time?

We start this research with a literature study. We use the theoretical framework to create a better understanding of the planning of the engineers and programmers that perform activities with a variable duration and contingencies (disturbing activities).

We analyze literature that is relevant for the planning and scheduling in Engineer-To-Order companies. Based on these outcomes, we identify the advantages and also the limitations of this literature. To overcomes the limitations, we take a look at literature related to the planning in other industries. We can compare the planning of engineers and programmers to the planning of operating theatres in hospitals.

The planning of operating theatres is based on the distinction between elective surgeries and emergency surgeries and contains some practices that can be useful for the planning of staff at Romias. Emergency surgeries are hard to predict. They will occur, but you don't know when, how often and how long it takes to handle them. Some of them have to start immediately, others can wait until a surgery is finished and will start as soon as a theatre becomes available. We can compare this situation to the disturbing activities that occur at Romias.

The goal of this theory is to minimize the overtime probability of operating rooms and other resources (surgeons, wards, anesthesiologists etc.). Table 1.2 summarizes the comparison between the literature and the planning of staff at Romias.

Planning of Operating Rooms	**Planning of staff at Romias**
Elective surgeries	Planned activities engineers / programmers in serial production / prototype building
Emergencies	Disturbing activities / Variability in duration planned activities
Goal: minimize overtime (probability) operating room	Goal: minimize overtime (probability) engineers / programmers

Table 1.2 Comparison between planning of Operating Rooms and planning of staff at Romias

Question 1: How does literature describe the planning and scheduling of staff in Engineer-To-Order projects/companies?

Question 2: What can we learn from literature that is related to the planning of staff in other industries, like the planning of operating rooms in hospitals?

Questions 1 & 2 are answered in Chapter 2.

We continue the research with a profound analysis of the current situation of the planning of engineers and programmers at Romias. We create more insight in the tasks that are performed by the engineering and programming staff and all activities that are related to the planning of projects and staff. Various sources of information will be used:

- Interview with the project manager about the planning procedures at Romias
- Interviews with engineers and programmers about the balance between planned and disturbing activities during their workday
- The daily/weekly planning of engineers and programmers
- The actual time (hour) registration of engineers and programmers
  - Compare planned hours and actual time registration
  - How many time is spent on disturbing activities?

The hour registration is used to keep track of all the activities that is performed by staff. Engineers and programmers are responsible for their own hour registration. The hour registration of some persons is more detailed than the hour registration of others. We require at least information about:

- Activities that an engineer / programmer performed (at least per 30 minutes)
  - Including the corresponding projects
- We explicitly ask engineers and programmers to keep track of the time that they spend on unplanned (disturbing) activities and the frequency of occurrence. The time that they spend on the disturbing activities can be rounded to 30 minutes in order to avoid rounding errors between the staff members.

With the help of these data, we want to find an answer to the following questions:

Question 3: How are the activities of the three different project types planned in the current situation?

Question 4: What are the (planning related) causes of the problem that Romias is not able to match the estimated and actual duration of engineering/programming activities in projects?

Questions 3 and 4 are answered in Chapter 3.

Based on the analysis of the current situation and the literature study, we can identify suggestions to improve the planning process. We will describe the possible solutions and the advantages and disadvantages. We want to know how the solutions contribute to the goal of this research.

To do so, we create a simulation model that simulates a project schedule and the planning of engineers and programmers. We use data from the current planning and estimate the values of unknown variables. We simulate different scenarios to create an optimal planning strategy.
In Chapter 4, we construct a model that approaches the current planning process of the engineering part of Engineer-To-Order projects. We simulate different scenarios that

potentially improve the planning in terms of lower processing times and higher work efficiency. We present the results of the simulation in Chapter 5. Question 5 is answered in Chapter 5.

Question 5: How can we change the planning of engineers and programmers at Romias to make it more efficient and more resistant to disturbing activities and variable duration of engineering and programming activities?

1.4 Research methodology

The data that we use and the interviews that we take must be valid and reliable to enable us to make the right judgments and conclusions. There are multiple threats to both the internal and external validity of the information that we want to use during our research.

Cooper & Schindler (2014) describe validity and reliability as follows:

- Validity: Does the test measure what we want? To what extent?
  - Internal – Do the conclusions we draw about a demonstrated experimental relationship truly imply cause?
  - External – Does an observed causal relationship generalize across persons, settings and times?
- Reliability: To what degree gives the measure consistent results?

1.4.1 Interviews

To create a better understanding of the involved stakeholders and their opinions, we perform a stakeholder analysis. We identify all the stakeholders and describe how they are affected by decisions and/or influence decision making. We place the identified stakeholders (regarding to planning and scheduling) in the stakeholder power-interest grid. (Figure 1.6)

1. Management of Romias
2. Owner of Romias
3. Customers
4. Engineers / Programmers
5. Project manager

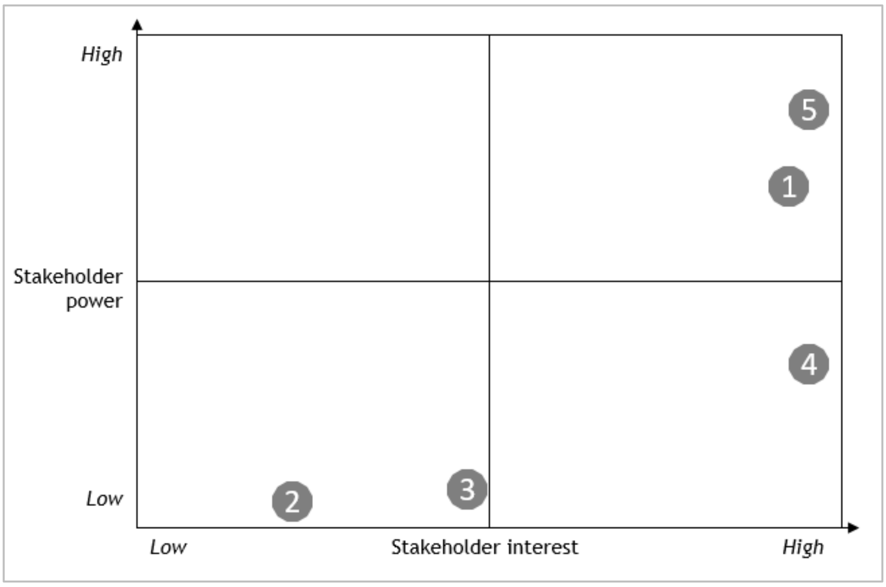

Figure 1.6 Stakeholder power-interest grid (Slack, 2010)

The management of Romias accepts new projects and discusses deadlines with the customer. Obviously, the manager wants to accept as many as possible project to make profits for his company. The owner of Romias had only one concern: projects should be profitable. His interested in the planning is low. Customers want in general a short deadline. The project manager has to make a planning for all the projects, given the agreed deadlines. The engineers and programmers can influence the planning, since they can estimate activity durations based on their experience. They may have conflicted interests compared to management. A lot of (new) projects can lead to high workload for example.

For the interviews that we take, this implicates that we always need to compare the given results with the results of other stakeholders that may have conflicting interests. By doing this, we decrease the effects of biased opinions of stakeholders.

1.4.1.1 *General information Romias and internal processes*

For this purpose, we interviewed the management of Romias. The interviews were in an informal setting and took place multiple times during the research. For these interviews, we prepared some questions about the systems that Romias produces and the internal processes. During the meetings, we made notes of the most valuable information that we retrieved. We had three meetings with a duration of 60-120 minutes. Besides these large meetings, we also had a lot of short/unplanned chats to conduct information in an informal way.
We didn't validate the information that we got from management with other stakeholders, since there a no conflictions opinions that can influence the outcomes of this research.

1.4.1.2 *Planning and scheduling procedures of engineers and programmers*

The interviews about the planning and scheduling of engineers and programmer had more structure and are used to create a better understanding of the current planning procedures and its limitations. We interviewed multiple stakeholders to create better insights in the problems of the planning process from multiple perspectives. This is a form of *face validity* that prevents that the opinion of one stakeholder influences the outcomes of the research when this opinion does not represent the real situation correctly.

Interviewed stakeholders	• Management • Project manager • Engineers
Subjects of the interview	• General information about planning processes • Bottleneck in planning • Responsibilities in creation and execution of the planning • Limitations of the current planning process • Causes of gap between expected and actual duration of activities
Duration	60-90 minutes
Setting	Interviews apart from each other, in an informal setting. We pretended to know nothing of the discussed subjects and asked a lot of supplementary questions.
Notes	A list of questions was prepared before the interviews. We used the same questions in every interview. We made notes of the answers that we used to describe the current planning processes and its drawbacks.

Validity	*Face validity* used by asking multiple stakeholders the same questions.

Table 1.3 Details interviews about planning and scheduling procedures

1.4.2 Data

There are multiple data sources that we use during the research. Table 1.4 describes the sources, validity, reliability and solutions.

Source	Validity	Reliability
Hour registration *Keeps track of time that staff spends on (planned) activities*	With the hour registration, we can check how much time an engineer or programmers spends on certain activities. However, these times do include the time that is used for small disturbing activities. It is hard to use the hour registration for a calculation of time spend on disturbing activities	Not every engineer / programmer keeps track of a detailed hour registration. Some of them specify their hour registration to 5-10 minutes, others round it up to 30 minutes or hours. This gives inconsistent results among the different staff members.
Pre-calculation *Specifies the estimated required hours to complete a project*	The hours that are needed per project activity are estimated by the project manager and engineers. Sometimes, the hours are multiplied by a risk factor, based on the instinct of one of them. The management of Romias checks the calculation afterwards and can reduce the hours of certain activities to make a better (cheaper) offer to the customer.	The major part of the calculation is based on the experience of the project manager and the engineers. When they don't have experience with a new engineering / programming task, don't seem able to make a very reliable estimation of activity duration.
Final calculation	The final calculation can help to create a better understanding of hours that are actual spend on project activities. However, a final calculation is not always made. It is not necessary, since customers pay a fixed price for a project, based on the pre-calculation. It is hard to determine the actual hours that are spend per activity, since the hours are not specified very well in the hour registration of engineers and programmer.	*See the reliability of hour registration.*

Table 1.4 Validity and reliability of used documents

We conclude that a lot of documentation that we use for this research is not very valid and reliable. To improve this, we ask staff to make their hour registration more detailed, and to keep track of the time that they spend on disturbing activities. We will check the correctness of the assumptions that we have to make by means of face validity: reflecting the extent of a measure with the stakeholders. (Hardesty & Bearden, 2004)

2 Theoretical framework

In this chapter, we analyze literature containing research that concerns the subjects of this study. We use the theoretical framework to create a better understanding of the planning of staff in Engineer-To-Order companies, in a situation where activity durations are variable and disturbing activities occur. We complement the literature study with theory from other industries to overcome the limitations of the literature about planning in Engineer-To-Order companies. Section 2.1 contains the planning and scheduling in an Engineer-To-Order environment. Section 2.2 describes literature about the planning of operating rooms in hospitals. This literature contains parts that can be used to overcome the limitations of literature about planning and scheduling in an ETO-environment. We conclude the literature study in Section 2.4.

2.1 Planning and scheduling in an Engineer-To-Order environment

Planning and control in the Engineer-To-Order (ETO) industry is difficult. Factors that make the planning difficult are uncertainties about:

- Project specifications
- Demand
- Lead times
- Process durations

However, a lot of companies in the ETO industry still make use of deterministic data in their planning processes. (Hicks & Braiden, 2000)

Little, Rollins, Peck, & Porter (2000) identified the key business processes for companies in the ETO industry, like Romias. They established a reference model that highlights the key processes related to planning and scheduling and the fulfilment of customer order. Figure 2.1 shows the reference model.

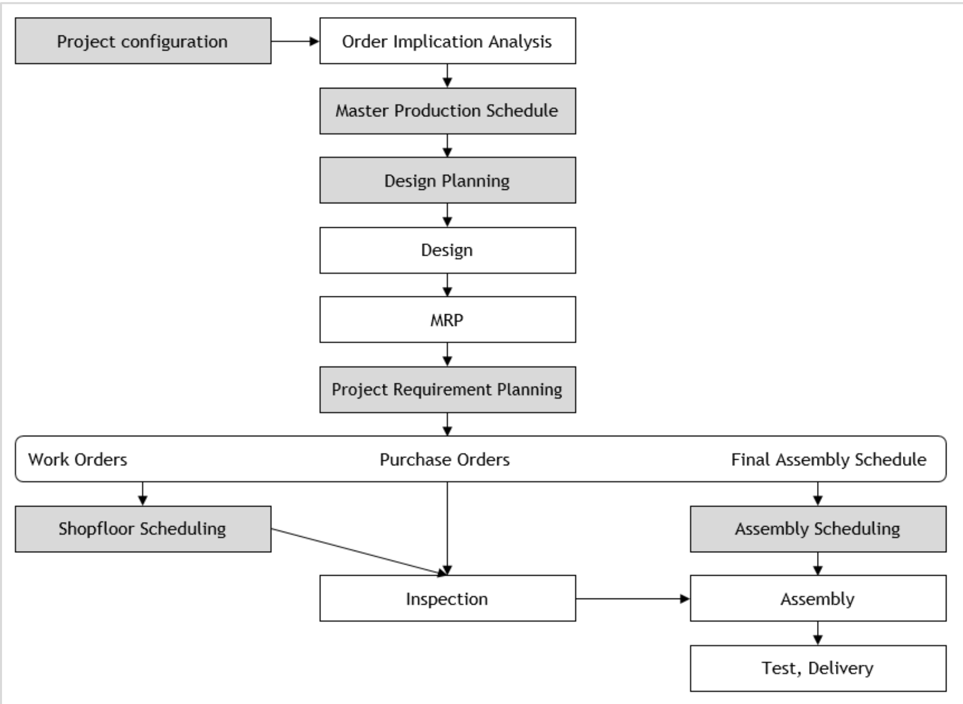

Figure 2.1 Outline of the Engineer-To-Order reference model (Little, Rollins, Peck, & Porter, 2000)

Project configuration

When a customer initiates an engineer-to-order product, the specifications / configuration of the project must be clear to both the customer and the producing company. "Omissions, inaccuracies or errors in the initial specifications and configuration of the product add to rework levels in both design and manufacture and commonly lead to part being manufactured late." (Little, Rollins, Peck, & Porter, 2000)

Master production schedule

To prevent that resources (staff, equipment, space) are overbooked and deadlines cannot be met, the load upon these resources should be measured even before a project request is accepted. This is a sort of Rough Capacity Planning (or Order Implication Analysis). "An assessment of the load upon the critical resources is vital to the maintenance of work flow and delivery dates." (Little, Rollins, Peck, & Porter, 2000)

Design planning

Design is essential in ETO companies. It commonly takes longer than the production/assembly of a project itself. Design includes engineering and programming of a project. The load on the relevant resources should be monitored and controlled very strictly. Design may not be broken up into smaller sub-parts. "The design capacity should be a product of available labor hours, resource utilization, labor efficiencies and labor skills."
Due to varying duration times of the design activities, many firms experience that it is difficult to express capacity in times.
However, only few designs are commonly completely new to a firm. This supports the idea of a modular approach of design activities: associate estimated times to comparable elements of earlier designed parts.

Project requirements planning

The planning of a project contains the confirmation of a due date, taking into account the current projects and the (forecasted) resource capacities. Insufficient planning of the project can lead to exceedance of the agreed deadline and/or excessive overtime. The schedule that is made in this stadium of the project is called the baseline schedule or pre(dictive) schedule. (Herroelen & Leus, 2005)

Shop floor scheduling

This part is in fact supporting the final assembly of a project. Sub-assemblies and other components also need a schedule, since late production / assembly of these parts can result in major delays in the final assembly. The progress of these activities should be monitored well.

Assembly scheduling

The final assembly is dependent on the assembly / production of sub-assemblies and other parts. Complete projects can be delayed due to the lateness of just one minor part. Due date adherence is also affected by rework in components or customized parts.

Integrated planning

Little, Rollins, Peck, & Porter (2000) furthermore highlight the importance of an integration of all described activities. The final product assembly sequence should be the driver for the other steps in the planning and scheduling of a project. When parts are delivered / assembled in the good assembly sequence, this improves the smoothness of the complete process. In order to do so, a form of back-scheduling is proposed: The assembly schedule is input for the shop floor schedule, which is input for the design planning etc.
Literature is unambiguously about the objectives of planning and scheduling of projects. Minizming the total project duration, overtime (costs) or lateness are in general the functions that are used to determine the quality of the planning and its outcomes. (Herroelen & Leus, 2005) (Little, Rollins, Peck, & Porter, 2000)

2.1.1 Planning and scheduling of activities with variable duration

All projects are confronted with uncertainty/variability. Main causes are:

- Information about the activities that have to be performed becomes available gradually and in a later stadium of the project. The master production schedule is already made.
- Variability on the shop floor. The shop floor schedule and assembly schedule are uncertain.

(Hans, Herroelen, Leus, & Wullink, 2007)

We will now continue with the definition of variability in activity durations and more detailed causes and possible solutions to deal with this variability.

2.1.2 Variability of activity durations

Hopp & Spearman (2008) describe the definition and causes of variable process times.
They link variability to randomness and probability. We can predict a process time, but the actual process time will not always be the same as the predicted time. It can be smaller or larger.

Mathematical explanation variability

Probability functions provide an overview of the behavior of a (random) variable. It is uncertain what value X the fuction will take on, but it always seems to tend to a certain value μ_x, the average. This can also be described as the expected value. The variance σ^2 is the expected value of the squared deviation from μ:

$$Var(X) = \sigma^2 = E[(X-\mu)^2]$$

When a probability function has a large variance, the probability that the true value is near to $\mu_{x,}$ is small. See the example in Figure 2.2. (Larsen & Marx, 2012)

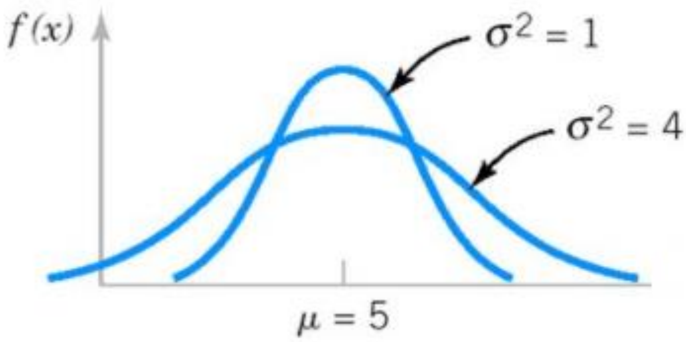

Figure 2.2 Example probability function

A distinction between controllable and random variation is made:

- Controllable variation: Decisions are made that cause variation.
- Random variation: This is related to events that cannot be controlled. Example are downtimes of machines or unforeseen activities in engineering / programming.

In order to deal with variability, we need to know what the causes of variability are:

- Natural variability: This type of variability occurs more in manuals processes than in automated processes. It is often related to an operator and does not include outages, setups and rework.
- Preemptive outages / breakdowns: Breakdowns occur also on the moments when you don't want them to happen. A good example is that engineers and programmers can be called away during planned activities.
- Nonpreemptive outages / setups: The difference with preemptive outages is that the occurrence of nonpreemptive outages can be partly controlled. This can be the replacement of worn tools for example.
- Rework: This is related to quality problems. An activity is performed and thereafter the quality of the outcome is checked. It can be that the quality is not sufficient and that some rework is required. A customized part that is based on 3D drawings can have slightly different dimensions in reality for example, which needs some rework in the engineering of that part.

(Hopp & Spearman, 2008)

Herroelen & Leus (2005) distinguish different approaches to deal with the uncertainty in the scheduling of projects:

- Reactive scheduling: Used when the predictive schedule does not anticipate to variability. When an unexpected event occurs, all affected activities can be shifted to the right (in terms of time) or all remaining activities are completely rescheduled. A new time span is created in that case.
- Proactive scheduling: Extra time for faults is already part of the scheduling process. This can be extra resources to re-execute tasks in the case a fault is made. Another method is to add idle time (slack) to overcome machine breakdowns or other failures. (Herroelen & Leus, 2005)

2.1.3 Disturbing activities

Disturbing activities affect the time that is available for planned project activities. However, do they also influence the duration of these planned activities? Stoop & Wiers (1996) state that planned durations of activities are often too optimistic. Disturbing activities result in a gap between expected and actual duration. They categorize the disturbing activities. (Table 2.1)

Type	Examples
Capacity	Machine breakdowns
	Illness of engineer / programmer
	Unavailability of tools
Orders	Unavailability of materials and drawings
	Fulfilment of sequencing rules
	Extra orders caused by scrap or rework
	Rush orders
Measurement of data	Gap between estimated and actual activity duration
	Capacity efficiencies

Table 2.1 Disturbing activity types and examples (Stoop & Wiers, 1996)

The disturbances related to capacity and orders are applicable to the production/assembly, while the category 'measurement of data' is the responsibility of a project manager and/or planner. (Stoop & Wiers, 1996)

Klassen, Russell, & Chrisman (1998) discuss the influence of disturbing activities on the efficiency and work productivity of employees. They make a distinction between normal times and standard times to perform activities. Normal times are calculated by timing a specific task (multiple times) and take the average of the different instances. The standard times include allowances for breaks, rests and delays. It is calculated by: $S_i = T_i \times (1 + a)$ where a = the allowance for rest periods breaks and other delays. (Klassen, Russell, & Chrisman, 1998)

Evers, Oehler, & Tucker (1998) add that engineers spend a minority of the daily available time to the planned core activities (30%). The rest of the time is used for distracting/disturbing activities:

- Meetings
- (Telephone) interruption
- Support activities
- Looking for information
- Hot priority tasks
- Documentation

On average, the engineers that were part of the research had 15 changeovers between these categories per day. To overcome the excessive variability and to simply work, several principles are mentioned:

- Give staff information about the impact that their work has on the total planning.
- Reserve time for engineers in which they can't be interrupted.
- Reserve a day per week in which no meetings can be planned.
- Standardize parts in design to support reuse.

2.1.4 Limitations of literature about planning and scheduling in ETO environment

We studied literature about the planning and scheduling of resources in the ETO environment. However, not all the principles are applicable to the situation at Romias. In this sub-section, we summarize the applicable parts and the limitations of the studied literature. (Table 2.2)

Category	+/-	Pros (+) and limitations (-)
Description of planning processes	+	Good explanation of the different processes of project planning: from the project identification to a (daily) schedule for staff and other resources. (Little, Rollins, Peck, & Porter, 2000)
Planning and scheduling of multiple project and activity types	-	Most firms are focusing on one production method (serial production or project based for example). Literature does not describe situations in which multiple production methods in one single company are applied. Literature about project planning is mainly focused on single-project organizations, and not on organizations that run multiple projects at the same time. (Hans, Herroelen, Leus, & Wullink, 2007)
Planning of activities with variable duration	+	Causes of variability in activity duration explained (Hopp & Spearman, 2008)
Disturbing activities	+	The literature describes the nature of the different disturbing activities that can occur and gives methods to deal with the overtime or to reduce the probability that they will occur.

Table 2.2 Applicable parts and limitations of literature about planning and scheduling in an ETO environment

2.2 Planning of operating theatres

As we explained in the section 2.1, not all the parts of the literature of planning and scheduling in ETO-companies is applicable to the situation at Romias, since it does not include the distinction between different production types (serial, prototype, contingencies). We therefore use theory form the healthcare sector, because it does include these differences.

2.2.1 OR days

Hans & Vanberkel (2011) describe that hospital manager strive for a high utilization of the operating theatres, the so-called OT utilization. They therefore introduce the principle of slack time. The slack time can be used and planned for emergencies or as a buffer for elective surgeries that have a duration that is above expected. Elective surgeries are the surgeries that are planned on forehand. The reserved capacity can be determined based on the desired overtime probability. A large amount of slack time means that the overtime probability and overtime costs are low. However, it can reduce the utilization of an OT, which is also costly. A workday exists of the expected duration of planned tasks and the slack time. (Figure 2.3)

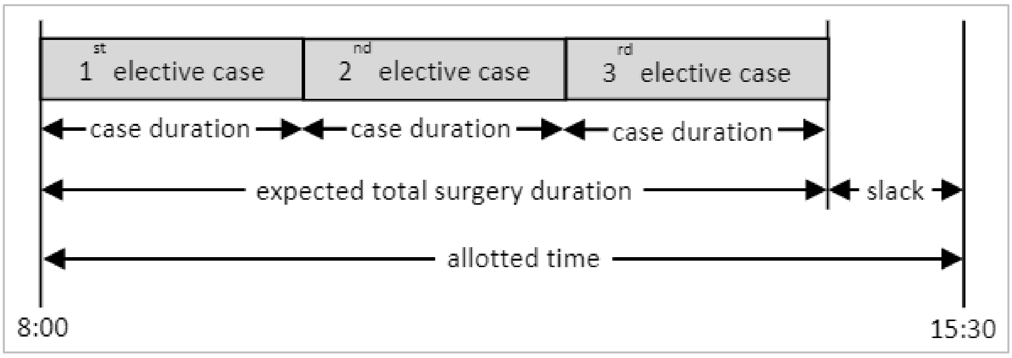

Figure 2.3 Timeline for surgical cases (Hans & Vanberkel, 2011)

Hans, Wullink, Van Houdenhoven, & Kazemier (2008) developed a model to assign elective surgeries to operating rooms whereby the operating theatre department is optimized and the total overtime is minimized.

Overtime can be prevented by adding slack to the planning of an operating room. The slack is determined on basis of the expected duration and variation of a surgical case.

The complexity of planning operating theatres is <u>variability</u>. This makes a planning very uncertain: There is a probability that the available time is not sufficient to complete all the planned surgeries, resulting in overtime.

2.2.2 Different surgery types and emergencies

Different surgery types have different expected durations and variabilities. Surgeries within the specialty Ear-Nose-Teeth are not that complicated and the probability that these surgeries have a longer duration (standard deviation / variation) than expected is relatively small. There are also surgery specialties whereby the surgeries are far more complicated and thus have a greater probability to have a longer duration than expected. These surgeries have a relative large standard deviation / variation.

We can compare this situation to planning of the engineers and programmers at Romias. A manager wants its resources to be utilized for 100%, but also needs the flexibility to schedule activities that need to be done immediately and occurring disturbing activities. Elective cases are comparable to the activities in serial production and prototype building. Emergencies are at Romias the disturbing activities. Reserve capacity is assigned to engineers and programmers to handle disturbing activities, but also the variable duration of activities in serial production and prototype building.

Sommers (2006) performed research about the planning of operations and emergencies at UMC. At UMC, a distinction is made between the prorities of emergencies. Not every emergency is such urgent that it has to be performed immediately. (Figure 2.4) The classification of the emergencies made the plannig easier, since not all emergencies had to be performed at the same. The number of interruptions in the planning/schedule of elective surgeries was decreased.

Romias does prioritize disturbing activities at the moment, but they may help to prevent distraction of the planning of engineers and programmers.

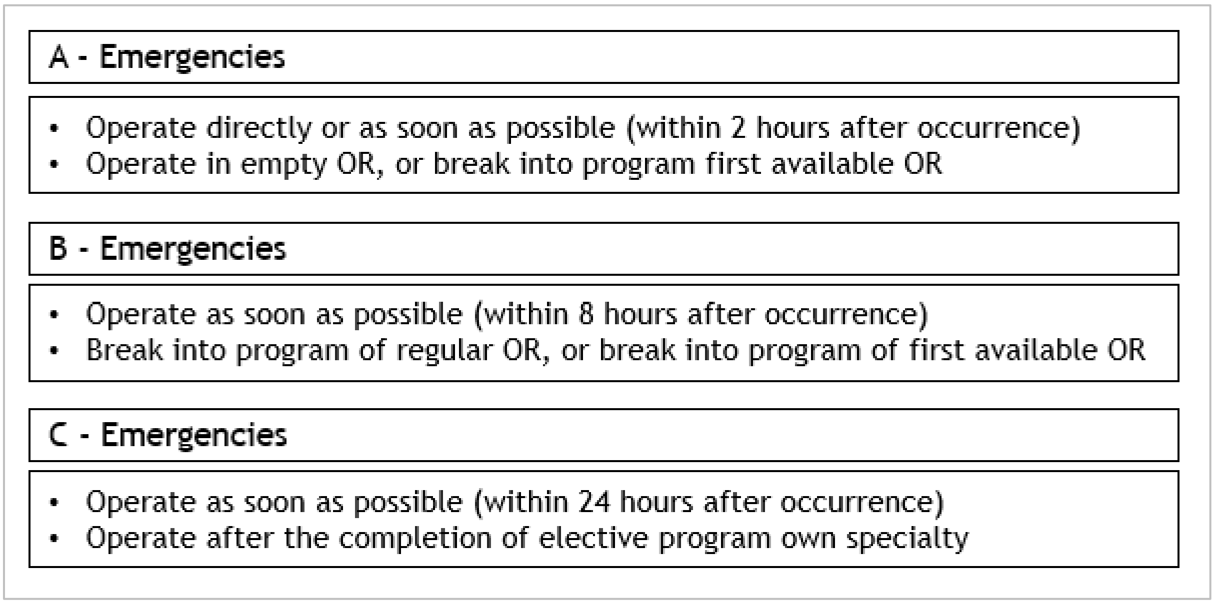

Figure 2.4 Priorities of emergencies (Sommers, 2006)

2.2.3 Dedicated emergency operating rooms

Hospitals have to choose whether to make use of dedicated emergency operating rooms. When they decide to dedicate operating rooms to emergencies, no elective surgeries are planned in these OR's. The utilization of dedicated emergency OR's is generally low, but does increase the probability that emergencies can be handled immediately after occurrence. (Hans & Vanberkel, Operating Theatre Planning and Scheduling, 2011)

The decision to make use of dedicated emergency rooms depends on:

- The frequency of emergencies
- Duration of all the emergencies
- (Extra) costs compared to other operating rooms
- Waiting times

Wullink, et al. (2007) state that the use of dedicated emergency rooms is not beneficial in terms of cost efficiency, OR utilization and overtime. Instead of using dedicated emergency rooms, some time is left free in (a part of) the generic operating rooms to handle the emergencies.

For Romias, the variables that are used to decide upon emergency rooms should be measured to make a decision about the use of dedicated service engineers/programmers for disturbing activities.

2.2.4 Preemptive operations

When an operation cannot be interrupted once it has started, it is nonpreemptive. This means that an emergency has to wait for the first operation to be finished before it can start. (Assuming that no dedicated emergency rooms are used and the generic operating rooms are planned with elective surgeries.) Activities are preemptive when they can be interrupted. (Roland, Di Martinelly, Riane, & Y., 2010)

Planned activities at Romias are preemptive. When disturbing activities occur, engineers and programmers do not necessarily have to finish the job that they are working on, before they can perform/solve the disturbing activity. However, when the engineers and programmers always start immediately with a disturbing activity directly after occurrence, this delays the activity that they were working on that moment.

A clear distinction should be made between disturbing activities that must be performed directly and those that can wait for a few hours or even days.

2.2.5 Performance indicators for planning & schedules of operating theatres

Literature describes several performance indicators / objectives to measure the quality of the planning and schedules of operating theatres:

- Minimizing the costs of opening an operating theatre and the costs of overtime. The number of operating theatres should be minimized to prevent inevitable fixed costs. Overtime costs extra money and indicates that capacity is insufficient and/or schedules are disrupted during a day. (Roland, Di Martinelly, Riane, & Y., 2010)
- Maximizing the utilization rate of operating room time, given a certain factor that is related to the overtime probability and used to calculate the reserved capacity. (Van Houdenhoven, Hans, Klein, Wullink, & Kazemier, 2007)
- Minimizing the total overtime of all operating theatres. (Hans, Wullink, Van Houdenhoven, & Kazemier, 2008)
- Maximizing the total free capacity of all operating theatres. This is the time that is left when the time of a normal workday is reduced with the expected duration of

surgeries and the planned slack. (Hans, Wullink, Van Houdenhoven, & Kazemier, 2008)

2.2.6 Limitations of literature about planning operating theatres

The theory of planning operating rooms has some limitations and is therefore not completely applicable to the situation at Romias:

- The expected duration of surgeries can be easier determined, based on historical data. A lot of surgery type are performed multiple times, while engineering and programming activities are performed less frequent.
- Planning of OR's includes the planning and scheduling of wards, surgeons and required tools. The planning of engineering and programming activities is bounded to less restrictions. (only engineer/programmer and an activity, assuming that other resources are always available)
- Surgeries are always completed at the same day of beginning and without interruptions (nonpreemptive). Project activities at Romias can have such a long expected duration that they have to be split over multiple days. Project activities can also be interrupted to perform a disturbing activity.
- Surgeries are not dependent of each other. Project activities are related to each other, there is a limited set of feasible sequences.

2.3 Framework planning and scheduling in an ETO environment

In section 2.1, we presented the ETO reference model (Little, Rollins, Peck, & Porter, 2000). The literature of planning and scheduling of operating rooms complemented the literature of planning and scheduling for companies in the ETO industry. We use this section to implement all the literature in the reference model. We therefore adjust the model in order to cover all the subjects mentioned in the previous sections. (Figure 2.5)

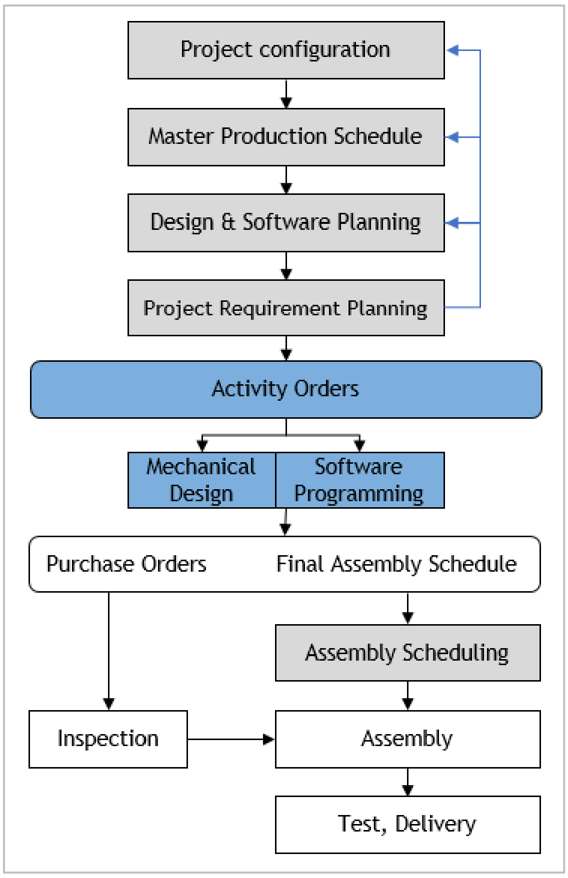

Figure 2.5 Modified ETO reference model, derived from (Little, Rollins, Peck, & Porter, 2000)

We added recursive arrows from project requirement planning to project configuration, since projects in ETO companies can be managed more effectively in an integrated manner. (Little, Rollins, Peck, & Porter, 2000)

Work Orders are replaced by activity orders and placed directly under the Project Requirement Planning. In the original model, Work Orders referred to the activities on the shop floor. We use a broader definition: Activity Orders can be applied to all the activities that are performed by engineers and programmers. That is why we placed Activity Orders above the design (Mechanical Design and Software Programming). Activity Orders contain all the information about the specific engineering and programming tasks, including the project, required resources and (expected) required times. Theory about the planning of operating rooms can be applied to Activity Orders when we compare an activity to an operation. An operation also has an expected duration, required resources and patient to whom the operation is assigned. The literature about operating theatre planning fits better because it can be used for the planning of simultaneous projects and multiple activity types. After the mechanical engineering, (customized) materials are ordered and once these are arrived, the assembly procedure can start. Finally, the project is tested and delivered to the customer.

2.4 Conclusions

In this chapter, we analyzed literature that is related to planning activities that are performed at Romias. For this study, we focus on the planning of staff, the engineers and programmers. This chapter gave answers to the following questions:

Question 1: How does literature describe the planning and scheduling of staff in Engineer-To-Order projects/companies?

Little, Rollins, Peck, & Porter (2000) established an ETO reference model that describes the different steps / levels in the planning of ETO projects. Difficulties in the planning of these projects are the result of uncertainties about the demand, specifications and variable lead times and processing times of the projects. The literature describes the causes of variability in the processing times and offers several solutions to deal with the variability and to be able to create a feasible planning.

Question 2: What can we learn from literature that is related to the planning of staff in other industries, like the planning of operating rooms in hospitals?

The limitation of literature of planning staff in an ETO environment, is the lack of planning activities from multiple types (prototype/ETO projects, serial production and disturbing activities). We therefore compared this planning to the planning of operating rooms in hospitals. The planning of operating rooms is done in such a way that it can deal with emergencies and variable duration of planned surgeries. In the same way, we can make the planning of engineers and programmers at Romias resistant to the occurrence of disturbing activities and variable duration of planned activities.

3 Current situation

This chapter describes the context of the research that we conduct at Romias, to get more insight in the internal processes. The main subjects of this chapter are the planning of the three different activity types and the causes of not meeting deadlines & gaps between estimated and actual activity durations. Section 3.1 describes the general process planning at Romias. Section 3.2 explains how engineers and programmers are planned at Romias. Section 3.3 contains more details about the planning of activities with a variable duration. Section 3.4 elaborates the occurrence and frequency of disturbing activities. Section 3.5 compares the current situation of the planning at Romias to the framework of planning is control that we presented in the previous chapter. Section 3.6 contains the conclusion of Chapter 3.

3.1 General process planning

Once a project starts, the engineers and programmers meet up to discuss the technical specifications of the robot system. The engineers begin with the mechanical engineering of the system, while the programmers develop the software (both robot movements and user interface).

When the engineering is finished, the materials are ordered. When all materials are delivered, the complete system is assembled by the engineers. After the assembly, the programmers test the system and the movement of the robot. The system is transported to the customer, where it is calibrated and tested again by the programmers.

More information about the robot systems that Romias produces can be found in Appendix B. The general planning cycle of a project and the processes are described in more detail in Appendix C.

3.2 Planning of staff

The planning of engineers and programmers is made by the project manager. He has insight in the projects and all the activities that have to be performed to complete them. A Gannt chart of a project is made, including deadlines and milestones. With these data, the project manager manually assigns tasks to engineers and programmers. This planning is not very detailed. It is more like: “Engineer A works on the mechanical engineering of project A in week 15, 16 and 17 and on the engineer of project B in week 17 & 18.” (Appendix D)

The planning of project related activities is based on the offer calculation (or pre-calculation) with estimated hours to perform specific tasks. These hours are multiplied by a risk factor (varying from 1 to 10) to determine the hours that are used in the offer. The function of the risk factor is to minimize the probability that the duration of a task is longer than calculated, and thus resulting in unforeseen costs. It is sometimes used because a lot of activities in Engineer-To-Order projects are hard to estimate on forehand. However, high risk factors are barely used in the final offer calculation, because it increases the price of a project with such amounts that the customer don’t want to pay it. Sometimes, high risk factors were applied to certain activities by an engineer, but reduced by management to make the offer price lower. Appendix E shows an example of the effort and cost estimation that is used to make an offer to a potential customer.

In the offer calculation, a breakdown structure of the project is made that describes all (sub-) parts of the project. Per part, a distinction is made between the hours and costs that are expected in the following categories:

- Engineering
- Materials
- Assembly
- Software

When high risk factors are applied to activities:

- The estimated costs of these activities are increasing;
- This affects the total estimated cost price of a project;
- It is more difficult to sell a project for a profitable price.

The planning of engineers and programmers is based on the estimated hours without applied risk factors. The probability that the planned number of hours does not match with the actual number of hours is very high, which can also be concluded from Table 3.1.

Competences of engineers and programmers
We distinct two different competences, the ability to perform:

- Project activities
- Disturbing activities

At Romias, engineers and programmer are widely employable. They are all able to perform both project and disturbing activities. Performing both activity types requires a lot of extra knowledge and experience compare to a situation in which some engineers and programmers only have to focus on project activities.

Responsibility
We mentioned that the engineers and programmers are responsible for the completion of certain tasks, but this doesn’t mean that they are responsible for the planning of a project. The progress of activities is currently barely monitored by the engineers and programmers themselves. They sometimes don’t even know when a phase of a project has to be completed. As a result, they don’t inform the project manager when they think that a project task has been delayed.

When disturbing activities occur, this affects the time that was planned for other activities. What happens with the time that was planned for serial production and prototype building? It can be that the engineer decides to work 1 or 2 hours longer on the same day, or that he performs that tasks later in the same week.

Bottleneck in planning
The bottleneck in the planning of a project is not clear. When the mechanical engineering is always the bottleneck in a project, it is easier to plan the other activities before and after the engineering. However, at Romias there are multiple project phases with a variable / hard to predict lead time. This makes it difficult to estimate the lead time of a project.

Buffer time
At the moment, no buffer capacity is planned that engineers and programmers can use to perform disturbing activities and activities that have a longer duration than expected. The planning is based on the estimated activity duration from the offer without applied risk factors. Planned activities must be performed at a later moment when disturbing activities occur, in the end resulting in delays of projects.

Sequence of projects
The progress of multiple projects is currently intertwined. Sometimes, projects start around the same time and have the same delivery dates. As a result, engineers and programmers sometimes work on two different projects on the same day: They work on project A in the morning and on project B in the afternoon for example.

Limitations of current planning process
During the analysis of the current planning process, we encountered the following problems / limitations:

- Estimation of hours in offer calculation is made under uncertainty;
- Planning is based on estimated duration of activities multiplied by the risk factor;
- No insight in the progress of activities;
- The project offer and the planning are made by different persons, while the hours in the offer (without applied risk factor) are directly copied and used for the planning;
- Planning is not integrated with the agendas of engineers and programmers;
- It costs a lot of time for engineers and programmers to fill in the hour registration accurately;
- Hour registration is not sufficient to give feedback on the planning;
- Disturbing activities are not planned;
- What happens with planned activities in case of the occurrence of disturbing activities? Are these completed in the evening/weekend/next week, or not completed at all? So, there are no rules to give disturbing activities a priority.

3.3 Variability in activity duration

In this section, we explain how the different activity types are planned.

3.3.1 Prototype building vs. serial production

The planning of engineers and programmers consists of the activities in serial production and prototype building. The disturbing activities are not part of the planning.

No systematic distinction is made between the different duration variabilities of serial production and prototype building. However, high risk factors are applied more often to activities in prototype building compared to serial production.

For both activity types, it holds that the expected duration of activities is the guidance for the project planning and the personal schedules of engineers and programmers. The current planning of project activities does not include time that can be used when an activity takes longer than expected. The estimated hours to perform tasks is directly copied to the planning: when 8 hours for a certain task are estimated for example, exactly 8 hours are scheduled. This implies that the productivity of engineers and programmers has to be 100% to meet the planning.

3.3.2 Engineering vs. programming activities

We have the detailed data of two projects that were build last year (2016/2017). We compared the estimated and actual hours of all the activities that are performed by engineers and programmers. (Table 3.1) The estimated hours are without eventually applied risk factors.

Veros	Estimated hours	Actual hours	Gap (hours and percentage)	
Programmers	108.5	356	247.5	328%
Engineers	906.5	2508	1601.5	277%

Knobbe	Estimated hours	Actual hours	Gap (hours and percentage)	
Programmers	137.5	515	377.5	375%
Engineers	387.5	1092	704.5	282%

Table 3.1 Comparison estimated and actual hours of programming and engineering activities

From these data, we can conclude that both engineering and programming activities can have a longer duration than expected. However, the underlying reasons are different for both functions. Programmers have to perform a lot of rework during the assembly phase of a project. Customized parts differ from the drawings, resulting in parts that not fit or holes on the wrong places in plates for example. Engineering of robot grippers or too much detail in drawings also result in more effort than expected.

Programmers have difficulties with programming the robot movements. It is very hard to predict the time that is needed to program these movements, which most of the times results in a higher actual duration than planned.

3.4 Disturbing activities

During a working day, engineers and programmers are faced with disturbing activities. These activities can cost them a lot of time. We analyzed the occurrence of disturbing activities. We measured both the frequency and duration of the disturbing activities of the engineers at Romias. We used the time registration of the engineers for one month and interviewed them to create an overview of the frequency and duration of disturbing activities on a working day. (Table 3.2)

As explained in section 1.4, the hour registration of engineers and programmers is not that detailed that we have a valid and reliable overview of the frequency and duration of the disturbing activities. We therefore confronted two engineers with the results of the hour registration and together we came to the used distribution of frequency and duration of disturbing activities. We used the analytic hierarchy process (AHP) to make comparisons between frequencies / durations of disturbing activities. For example: The probability that the duration of a disturbing activity is between 10 and 30 minutes is 3 times higher than a disturbing activity that has a duration between 30 and 60 minutes. (Goodwin & Wright, 2009)

Assumptions:

- The used month is standard and holds also for other months;
- Same data holds for the programmers as well, the hour registration didn't show deviant results.

Number of disturbing activities on a day	Probability
0	2.9%
1	11.6%
2	17.3%
3	28.9%
4	20.2%
5	14.5%
6	2.9%
7	1.4%
8	0.3%

Duration (minutes)	Probability
0-10	51.4%
10-30	30.9%
30-60	10.3%
60-120	5.1%
120-180	1.5%
180-240	0.5%
>240	0.2%

Table 3.2 Frequency and duration disturbing activities engineers

We combined this information to create an overview of the total duration of disturbing activities for an engineer/programmer on a working day, including the corresponding probabilities. This table can be found in Appendix F.
We used these data as input for a Monte Carlo simulation to create a graph that shows the number of minutes that an engineer spends on disturbing activities on a working day. We simulated 5000 days, since this is a reasonable large number. We increased this number, but this didn't affect the results (average minutes spend on disturbing activities). Figure 3.1 shows the result.

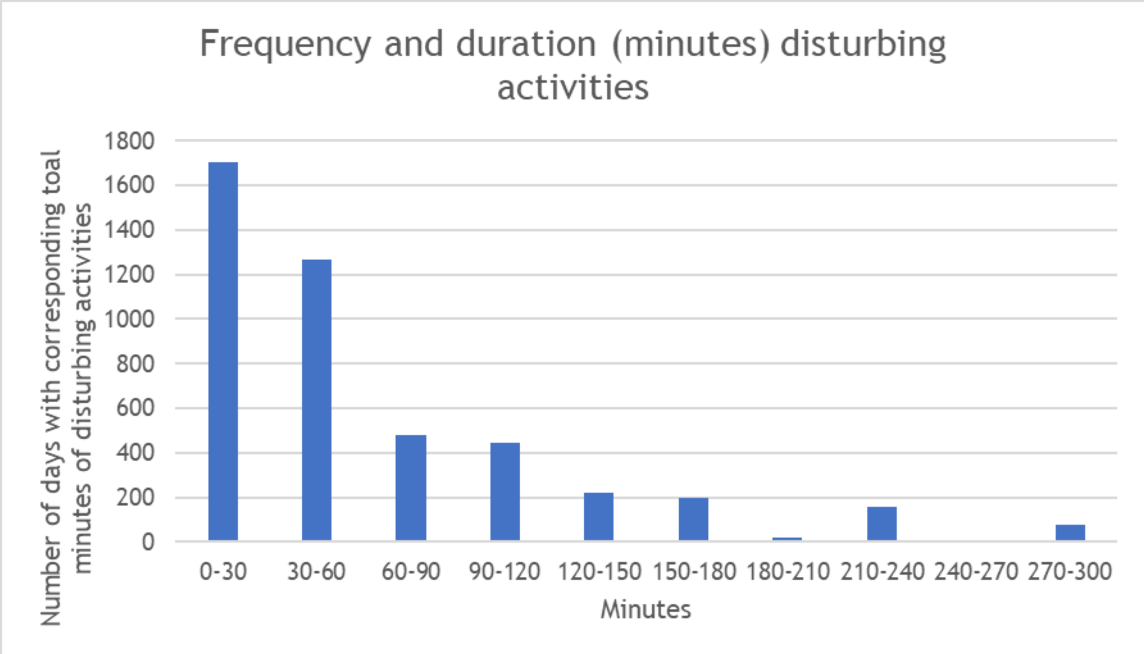

Figure 3.1 Frequency and duration of disturbing activities

The histogram presents the outcomes of the simulation. Some intervals have 0 observation, since the combination of frequencies and durations had no results in these categories.

The mass of this distribution is concentrated on the left and the graph is skewed to the right. The probability that an engineer spends more than 60 minutes on disturbing activities is 35%. Due to the outliers with a very high duration, the average time spend on disturbing activities is 99 minutes per person per day.

The limitation of this graph is that it is based on the data of Table 3.2. The data from hour registrations was not sufficient enough to create a clear overview of the time that is spent on disturbing activities.

3.5 Framework planning and scheduling applied to Romias

We compare the current planning and scheduling processes at Romias to the established model from Chapter 2.

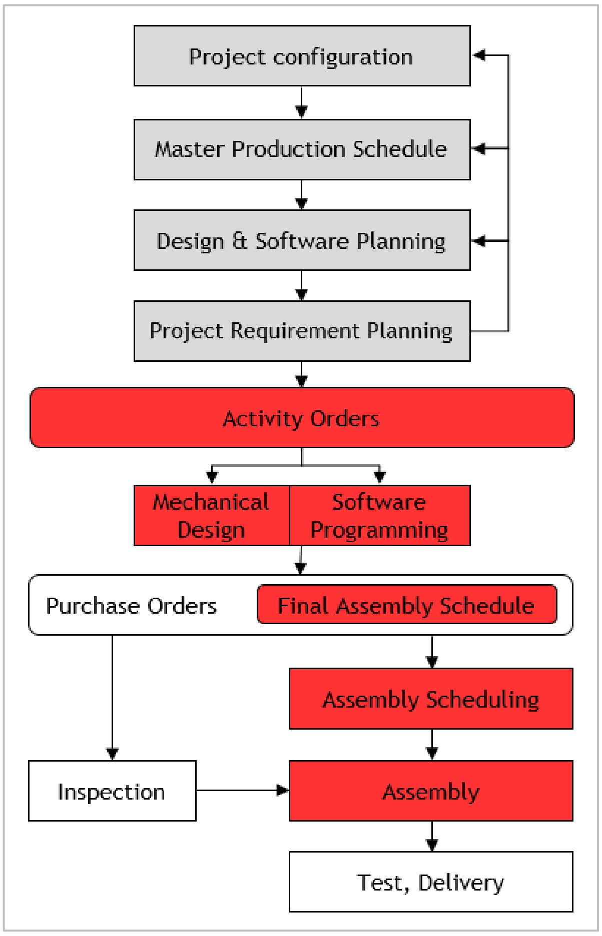

Figure 3.2 Modified ETO reference model, derived from (Little, Rollins, Peck, & Porter, 2000)

When we look at the reference model and the planning of engineers and programmers at Romias, we conclude that the planning of projects and the forthcoming project requirements seems sufficient. However, the planning and scheduling procedure(s) stop once the programmers and engineers got their weekly planning at the beginning of a new project.
No activity orders are made that can be used to keep track of:

- Progress of the activity
  - Estimated activity duration
  - Link with actual duration
  - Deadline
- Relation with other activities
  - What are the consequences when this activity is not completed in time?
  - How is this activity linked with other activities?

Most problems are related to the engineers, since multiple engineers can work on different parts of a project. Good communication is needed to prevent mismatches.

The assembly process starts when mechanical engineering is finished and all the required materials are delivered. No assembly schedule is made for the engineers that are carrying out the assembly process. This makes it hard to keep track of the progress of the complete assembly process and record valuable information about durations for similar assembly activities in the future.

3.6 Conclusions

This chapter described the current situation of the planning of engineers and programmers at Romias. We analyzed the complete planning cycle of projects at Romias: from project tendering to the delivery of a robot system at the customer. We focus on the planning of engineers and programmers.

Question 3: How are the activities of the three different project types planned in the current situation?

The current planning of engineering, programming and assembly activities in prototype building and serial production is based on estimated required hours, multiplied by a chosen risk factor. The hours that are used in the offer are manually copied to the planning.
The risk factor is more often applied to activities in prototype building compared to activities in serial production. However, no distinction is made in the different variabilities of process durations in both project types. The disturbing activities are not implemented in the current planning.

Question 4: What are the (planning related) causes of the problem that Romias is not able to match the estimated and actual duration of engineering/programming activities in projects?

We found some limitations of the current planning procedure and causes of the problem that engineers and programmers at Romias can't keep their planning:

- There is no insight in the progress of planned activities;
- It is not clear who is responsible for the completion of a planning;
- The offer calculation and the planning are made by different persons, while the hours used in the calculation are needed to make a planning;
- Engineers and programmers spend a lot of time on disturbing activities, while they should work 100% of their time on planned project activities according to the planning;
- Actual duration of project activities takes often longer than predicted, for both engineers and programmers.

In the next chapter, we present a model that simulates the current planning process and can be used to improve the planning by altering parameters.

4 Improvement of the planning process - model construction

Based on the analysis of the current planning process and the literature study, we now want to identify improvements that contribute to the research goal: reducing the overtime probability and prevent a large gap between estimated and actual hours to complete project activities. Section 4.1 contains the model selection procedure. Section 4.2 describes the model formulation. Section 4.3 shows how we validated the outcomes of the model. Section 4.4 describes the limitations of the model, since it is a simplification of the actual situation. Section 4.5 contains the conclusions of Chapter 4.

4.1 Model selection

In order to test proposed solutions, we use a model that approaches the current situation. By changing certain parameters and decision rules, we can check the effect of solutions compared to the current situation. We first select the right model type.

Law (2007) describes different ways to analyze a system. (Figure 4.1)

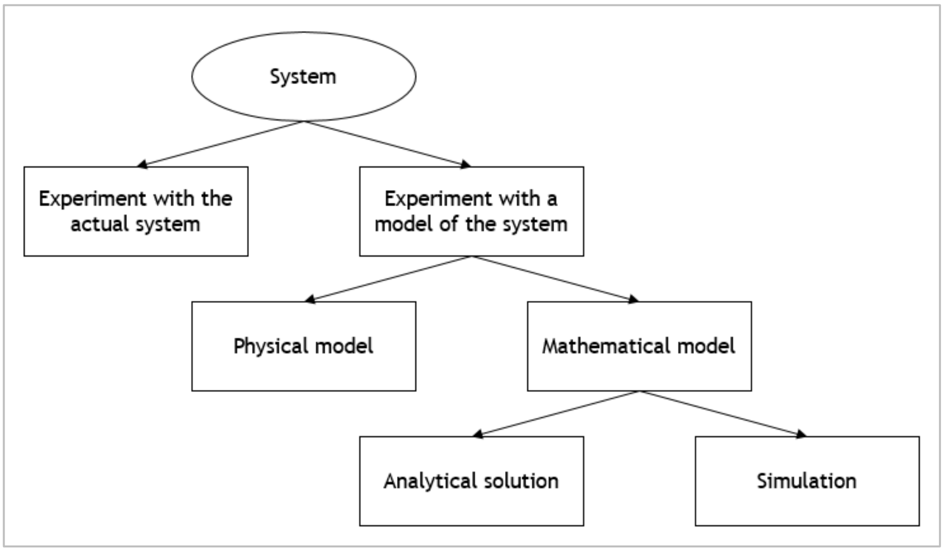

Figure 4.1 Ways to study a system (Law, 2007)

Experiment with the actual system vs. experiment with a model of a system

It is not feasible to test the proposed solutions immediately with the actual system. When we alter the planning procedures, it would take a long time before we can measure the results. It would also be disruptive for the system when we alter the procedures after each project to check the effect of other potential improvements or a combination of potential solutions. It will cost less time to experiment with a model. In that case, we have to make sure that the model reflects the system accurately and therefore we check the validity of the model. (Section 4.3)

Physical model vs. mathematical model
Planning processes cannot be made physical, like scale model of buildings, vehicles, tool etc. We use a mathematical model that represents the logical and quantitative relationships of a system.

Analytical solution vs. simulation
An analytical model is suitable when the model is so simple that exact solutions can be obtained with paper and pencil. Most systems are too complex for this. The model must be exercised numerically to see how the inputs affect the output measures of performance. This can be done with a simulation study. (Law, 2007) Drawback of a simulation is that it can only approximate the actual system. It is abstract and in most the times a simplification of reality. The simulation should always be developed and validated for a known set of objectives. (Law, How to build valid and credible simulation models, 2008)

The best way to model the planning and scheduling procedures at Romias is therefore a simulation of the current situation in which input parameters can be altered to see the effects on the output measures. A lot operating room planning studies and planning methods for projects are based on simulation models. (Hans & Vanberkel, Operating Theatre Planning and Scheduling, 2011) (Fernandez, Armacost, & Pet-Edwards, 1998)

Law (2008) established a seven-step approach that can be used to build a valid and credible simulation model. We use this approach to build a simulation of the planning of engineers and programmers at Romias.

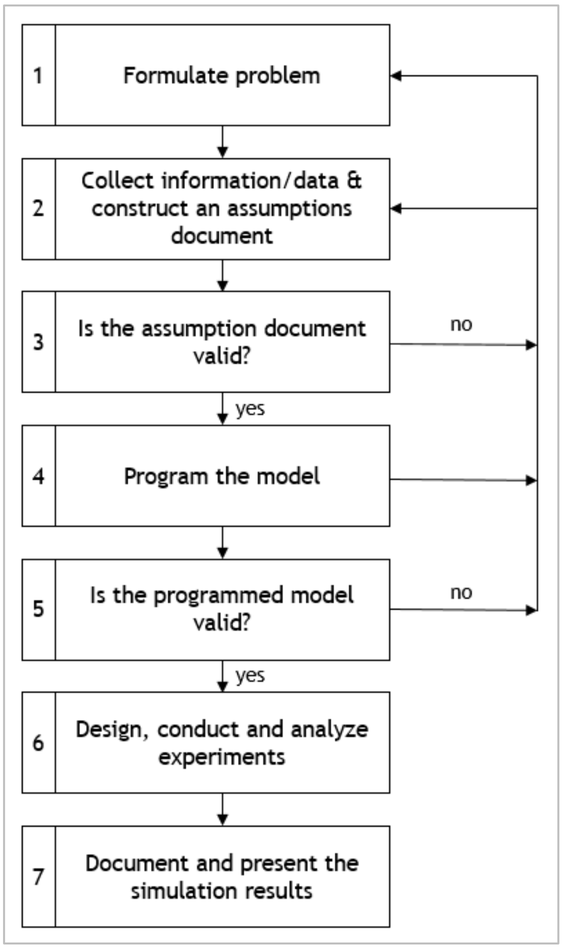

Figure 4.2 Seven-step approach for a simulation model (Law A., 2008)

4.2 Formulation of the model

This section describes the simulation model that we made. It gives insight in the modeled processes, the decisions that we make, the required input and the relevant output.

4.2.1 Model overview

The simulation model is used to provide information about:

- The actual time engineers and programmers are working on planned project activities
- The occurrence of disturbing activities
- The time that is needed to perform the disturbing activities
- Influence of disturbing activities on the duration of planned project activities (switching times)

By running different scenarios of the model, we aim for a reduction of:

- Throughput times of projects
- Work that engineers do in overtime
- The number of projects that is delivered after the agreed due date

We simulate projects that Romias performed in the last years, based on the data of available engineers and programmers, the expected and actual duration of planned project activities and the occurrence of disturbing activities.

Data about the project activities that are performed by programmers is very limited. They develop software that is not related to one specific project, but can better be described as a continuous process. We therefore choose to only model the engineering part of a project.

Section 2.1.1 outlined the Engineer-To-Order reference model. (Little, Rollins, Peck, & Porter, 2000) In the simulation model, we use the project specifications to simulate the progress of the project activities and the time allocation of engineers. In fact, we use the expected activity durations of projects and run these projects to see what this means for the activities of engineers and the progress of the projects.

Figure 4.3 shows the process flow of the simulation model.

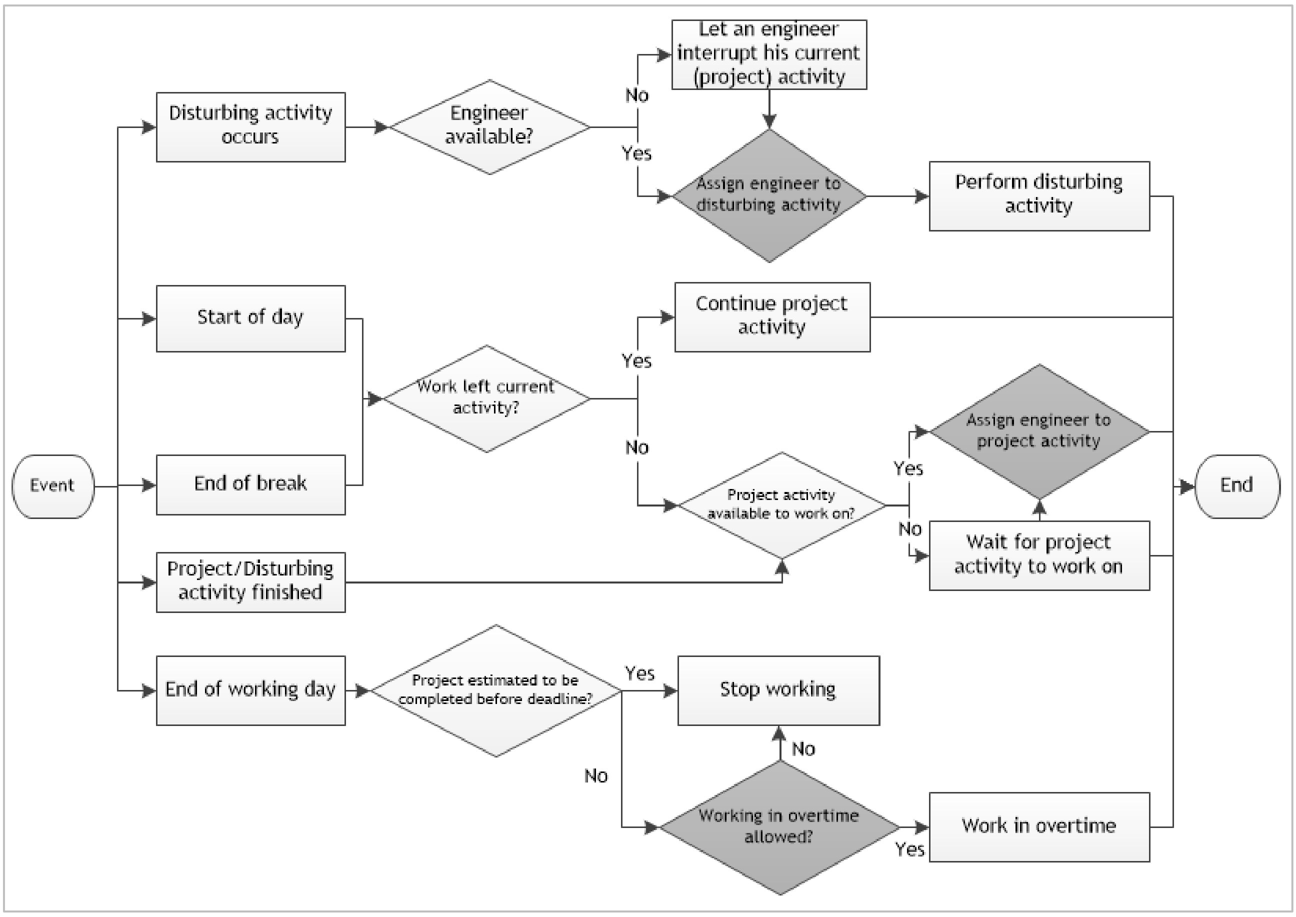

Figure 4.3 Process flow simulation

From the perspective of the engineers, there are four events that trigger a decision:

- The occurrence of a disturbing activity
- Start of a working day / Restart after the break
- Completion of a project activity or disturbing activity
- The end of a working day

Engineers are in general working on project activities. Depending on its complexity, a project consists of 5 to 8 activities that are performed in sequential order. When a disturbing activity occurs, an engineer has to perform this activity immediately. Switching between activities costs time and influences the throughput times of projects. When the completion of project activities is delayed, there is a possibility to make use of overtime to prevent or reduce delayed delivery of the project.

4.2.2 Assumptions

The model is a simplified representation of the actual situation at Romias. We therefore make some assumptions:

- We only model the internal processes at Romias, from the start of the engineering phase until the completion of the assembly;
- The expected duration of the project activities is normally distributed;
- Both project and disturbing activities are performed by one engineer;

- Capacity of tools, equipment and other resources is infinite. We only look at the engineers and their capacity;
- Engineering activities of a project are performed sequentially;
- Disturbing activities only occur during the standard working hours of Romias;
- The probability that a disturbing activity occurs is the same on every day;
- We use a standard working week of 5 days. Holidays are not incorporated.

4.2.3 Model output & Performance indicators

The output of the model consists of the results of the execution of the planning. To measure the performance of the simulation and to compare different scenarios, we use three performance indicators.

1. **Throughput time (THP)**

We define the throughput time time as follows:

$$THP\ (days) = completion\ date\ of\ project - start\ date\ of\ project$$

The THP gives us more insight in the completion time of a project. The THP is a good indicator to compare different scenarios. By changing the number of engineers, their competences, or the overtime that can be used, the THP will change. This contrasts with the processing time for example. The processing time will be the same in the different scenarios. Our aim is to minimize the THP.

2. **Work ratio engineers**

When it comes to the performance of engineers, we are interested in their work ratio. We define the work ratio per engineer as follows:

$$Work\ ratio = \frac{total\ time\ worked}{total\ available\ time}$$

When the work ratio of an engineer is low, this might indicate that there are too many engineers for the amount of work that is available. It is also possible that the engineer has not the right competences to have enough work. We aim to maximize the work ratio of engineers.

3. **Switching time**

Switching moments occur when an engineer switches from one activity to another. When an engineer starts our resumes an activity at the beginning of the day or directly after the lunch break, we also count this as a switching moment.
We aim to minimize the total number of switching moments (and therefore the total amount of switching time) of the engineers, since switching moments reduce their productivity.

4. **Lateness of projects**

We compare the completion date of a project with the agreed due date to measure the lateness of the project. We calculate the probability that a project will be completed after the due date and the average number of days that a project is delivered after the due date (tardiness)

a. Probability that project is delivered too late

$$\%\, projects\ that\ \ exceed\ deadline\ = \frac{number\ of\ projects\ completed\ after\ due\ date}{total\ number\ of\ projects}$$

b. Lateness

$$Lateness = \max\begin{cases} 0 \\ completion\ date - due\ date \end{cases}$$

4.2.4 Decisions

During a simulation run, multiple decisions are made. This section explains these decisions and how they are made.

How are planned activities assigned to resources?
A worker pool contains all the engineers that are available. They all have their own competences: Engineers can perform project activities and can solve disturbing activities. In the current situation, all engineers and programmers are able to solve disturbing activities and to perform project activities. Engineers are randomly assigned to project activities when more than one engineer is available. It is not necessary that one specific engineers performs all the activities of a certain project.

When must a disturbing activity be performed?
In the current situation, there is no clear distinction between high and low priority disturbing activities. As a result, all disturbing activities are performed immediately while this is not necessarily needed. When all engineers are occupied (performing project activities), a (random) engineer with the ability to perform disturbing activities interrupts its activity to first perform the disturbing activity.

Which resource performs a disturbing activity?
An available engineer with the ability to perform disturbing activities is randomly selected to perform the disturbing activity. When all engineers are occupied (performing project activities), a (randomly selected) engineer with the ability to perform disturbing activities interrupts its activity to first perform the disturbing activity.

When is a resource allowed to perform activities in overtime?
When the duration of planned project activities is longer than expected, and/or disturbing activities are causing a delay of the project(s), overtime can be used to prevent or reduce this. For the standard scenario, we do not allow the engineers to work in overtime.

4.2.5 Model input

For the input of the model, we gathered data and fitted this to theoretical distributions if needed. In some cases, we use empirical distributions that are based on historical data Input for the model consists of:

Time

The model simulates actual time. A workday starts at simulation time 8.00 AM and ends at 4.30 PM. The standard breaks between 12.30 and 1.00 PM are also part of the model. The model keeps track of the weeks, the day in the week and the total number of days since the start of the simulation.

Project activities

We simulate the engineering process of two recently performed Engineer-To-Order (prototype) projects, based on historical data from the first quarter of 2017. We refer to these projects as project 'A' and project 'B' (Appendix G) We use the activities that are part of the engineering process. The project activities are performed in a fixed sequential order. An activity can start when the preceding activity is finished.

The expected duration of project activities is the estimated duration of the activities without applied risk factors. Instead of the risk factors that Romias applies to activities, we model variability by using the normal distribution. (Appendix H)

We also use the due dates of the projects that we simulate to determine their lateness and tardiness. The deadline of project A is 118 days after the starting date, the deadline of project B 117 days after the starting date.

Disturbing activities

Frequency, duration and priorities of disturbing activities. (Section 3.4) The arrival of disturbing activities is modeled as a Poisson process.
In the initial model, disturbing activities have a higher priority than project activities and have to be performed immediately. When no engineer is available, an engineer interrupts its project activity to first perform the disturbing activity.

Switching times

Switching times influence the duration of an activity after switching from a previous planned or disturbing activity. Since we do not have exact data about the influence of switching between activities on the work efficiency of engineers, we assume for the standard scenario that the switching time is 10 minutes per switching moment.

Engineers

- Capacity

  We use the actual capacity of engineers during the period of the simulated projects. This mean that we make use of 3 engineers working fulltime (40 hours per week) at Romias. We assume that they are able to work in overtime when needed.
- Competences

  We distinguish two competences: Standard engineering activities (project activities) and disturbing activities. In the initial model, all the engineers have both competences.

4.2.6 Technical implementation

We choose to perform a terminating simulation. This means that parameters are defined based on initial start and stopping conditions. Knowledge about the long-run behavior of normal operations (non-terminating simulation) is less interesting, since the operations at Romias vary from time to time. Appendix J describes how we programmed the model in *Plant Simulation*.

In the model, we simulate multiple runs. A run in the model consists of the execution of all the projects (one single time). We specify the number of runs to be able to draw the right conclusions from the results of the simulation. We therefore take the processing times of project A and evaluate the average throughput time per run. (Figure 4.4)

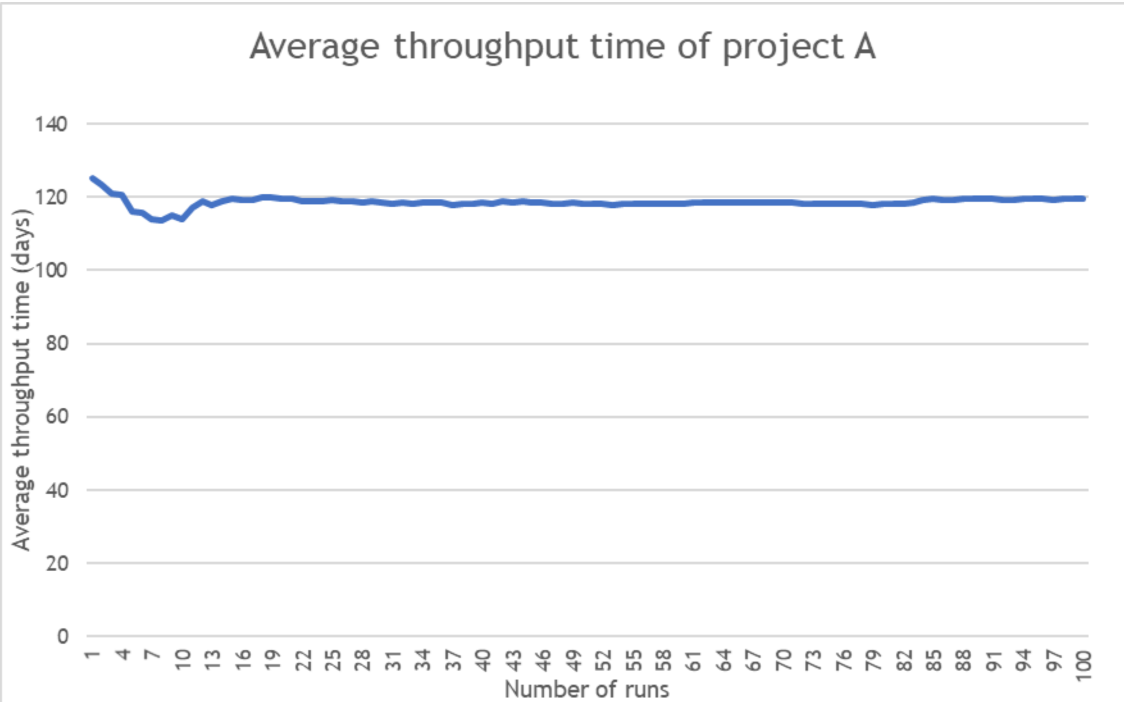

Figure 4.4 Determination number of runs

Based on the confidence-interval approach (Appendix J), we conclude that we need 25 runs, which means that we simulate every project 25 times. We assume that the other projects display similar characteristics as project A and that we don't need more runs to withdraw accurate conclusions about those projects.

4.3 Verification / Validation

We validate and verify our model to ensure that the model and its results correspond with the reality. Verification is done during the programming of the model in Plant Simulation, while validation of input and results of the models is done both before programming the model and afterwards. (Figure 4.5)

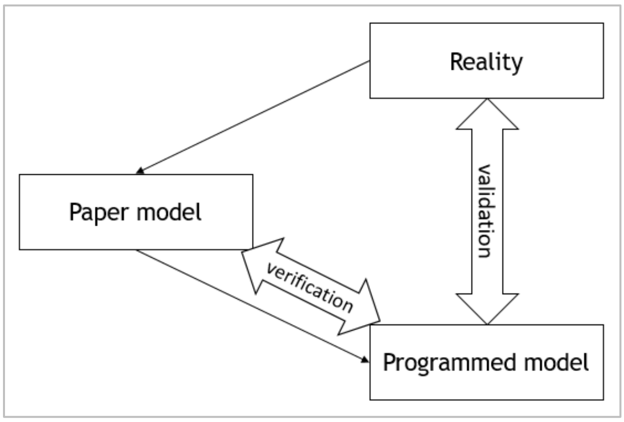

Figure 4.5 Validation & verification of model (Law, 2007)

Verification

We start with building a very simple, working, model and add more complexity (data, formulas) step by step. Afterwards, we debug the programmed model with the implemented debugger of Plant Simulation.

Validation

Law (2007) describes several methods to validate the programmed model. We use *face validation* to check the output of the model and to check whether it is in line with the real situation. We do this by asking the management of Romias to review the results of the model and check whether these results are reasonable.

We also validate the model with *results validation*, by comparing the output of the model to data from the actual system. We do this with the throughput times of project. Figure 4.6 shows boxplots of the throughput times of the projects A and B.

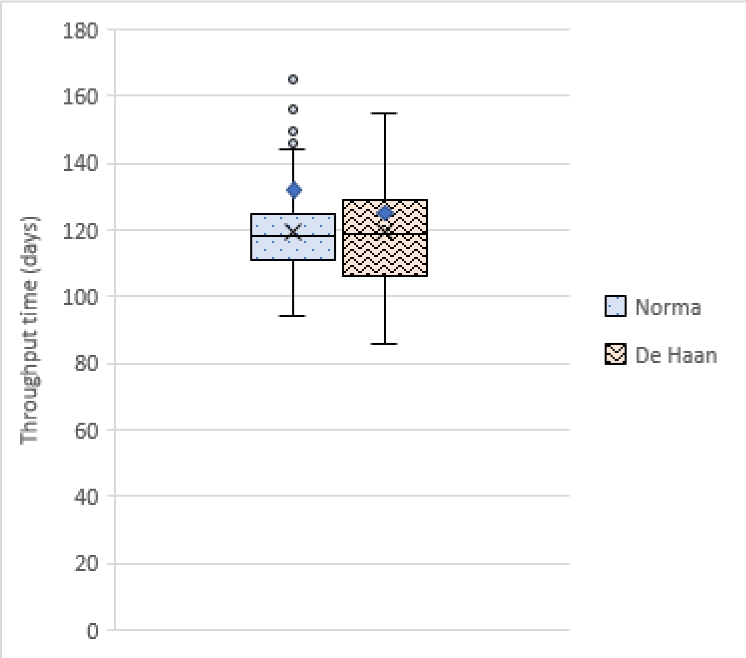

Figure 4.6 Throughput times projects A and B

The average THP of project A is 118 days, the average THP of project B is 119 days. However, we conclude that the THP of both projects has a high variability. We expected this, since the duration of project activities is hard to estimate and is subjected to high variability as well. The actual completion date of project A was 133 days after the starting date, the completion date of the project B was 125 days after the starting date. The boxplots of Figure 4.6 contain these values, which indicated that the model gives results that are comparable to the actual situation. The outcomes of the model can be a bit more optimistic than the real situation, since we assume that the engineers are working 40 hours per week and never are sick or go on holiday. Section 4.4 describes further limitations of the model.

4.4 Limitations of model

Limitations of the programmed model are in many occasions the result of lack of appropriated data. The expected and actual duration of engineering activities of the used projects consists of limited data. It is hard to identify the actual duration of project activities, since Romias does not keep track of the progress of projects in a very detailed way. For Romias, there is no direct need to do, because projects are sold for a price that is determined before a project has even started. Via the hour registration of engineers, we can search for the time that they spent on certain activities, but this does not provide a complete overview of the hours that engineers used to perform an activity. We therefore kept track of the hours that engineers used for activities of two projects that were engineered in the first months of 2017. We compared these data with the estimated hours that were used to make a planning.

We do not have actual data about the time that is wasted during a switching moment. We choose to add a fixed number of minutes to the duration of an activity as ‘set-up time’.

However, we do not exactly know how much time we have to add. We also don’t know whether the switching time is equal for all the different planned and disturbing activities.

In the model, project activities can only be performed once at a time, except for the assembly. This doesn’t happen in practice, but for the model this can result in waiting time for a project or engineer.

We modeled that the probability of the occurrence of disturbing activities is the same on every moment of the working week, while there can be peak moments in the actual situation. There can only occur one disturbing activity at a time. The next disturbing activity can only ‘arrive’ when the previous one is completed.

We modeled that engineers are working 40 hours per week and that they are always available to work in overtime. We did not model days off and illness for example.

4.5 Conclusions

This chapter described a model to simulate the current planning processes of engineers and programmers at Romias. A simulation study seems to be the best way to model a simplified representation of the real situation. We use the simulation model to simulate an execution of the engineering parts of some projects that Romias worked on recently. The model should give us insights in the actual duration of projects, the throughput times and the occurrence of disturbing activities and switching moments.

We verified and validated the construction of the model and concluded that there are some limitations that can possibly have a negative effect on the outcomes of the model. In other words, it makes it harder to approach the situation as it is in practice.

We continue in Chapter 5 with the results of the model as described in this chapter. We also simulate scenarios in which we change some input variables of the model. The results of these scenarios can help Romias to improve their planning procedures.

5 Improvement of the planning process - numerical results of model

There are several scenarios that we run to improve the planning of the engineers and programmers. Section 5.1 describes the interventions that we applied to the model in order to measure potential improvements. Section 5.2.1 contains the numerical results of the standard scenario. Sections 5.2.2 – 5.2.5 contain the results of the four different scenarios that we simulated. The results of these simulations can give us more insights in the effects of changing the number or composition of engineers for example. This information can help Romias to create a better understanding of the planning processes and execution of their planning. It also shows were the planning of engineers could be improved. Section 5.3 contains the conclusions of this chapter.

5.1 Experiment design

This section describes the scenarios that we perform with our simulation model. The scenarios are interventions of the model, in which we change the input parameters of the standard model. With these interventions, we want to reduce the throughput time of projects and their lateness / tardiness.

5.1.1 Selection of scenarios

The input parameters that we can adjust are:

- Number of engineers
- Competences of an engineer
- Allowed number of hours overtime per engineer per week
- Priorities of disturbing activities

In the scenarios that we simulate, we want to check the effects of adjusting these parameters on the performance of the engineering process. The number and competences of engineers are examined in scenario 1 and scenario 2. Scenario 3 describes the effects of working in overtime. In fact, this scenario shows how many time extra is needed to complete projects before agreed deadlines. This can also be achieved by adding an extra engineer (full-time or part time) to the staff. The last scenario is about prioritizing the disturbing activities. We do not simulate scenarios in which we make further combinations of adjustments to the input parameters, we assume that the results of the scenarios are positively correlated. We now continue this section by explaining the scenarios in further detail.

5.1.2 Standard scenario

We start with a simulation that is based on the current planning processes of engineers and programmers. This includes the following rules:

- There is no distinction in the priorities of disturbing activities. All disturbing activities have to be performed directly. A random engineer or programmer is selected to perform the disturbing activity;
- All engineers and programmers are able to perform both project and disturbing activities;

- Number of engineers is 3;
- The number of projects that are performed at the same moment is 3;
- Engineers do not work in overtime;
- Per project activity, an engineer is selected based on availability. This means that the engineering activities of a project can be performed by multiple engineers;
- Switching time is 10 minutes.

5.1.3 Intervention I – Competences of engineers

Engineers and programmers are widely employable. They perform both planned and disturbing activities. This has some disadvantages:

- A lot of switching between activities, which costs switching time.
    - Better to complete activities before starting another
- Staff needs extra knowledges to be able to solve breakdowns for example
- Planned activities cannot be completed without interruptions, not efficient.

To overcome these disadvantages, we change the composition of engineers in terms of competences. We run scenarios in which we replace 1 or 2 engineers by engineers that can only perform project activities. This reduces flexibility, but these engineers can work without all the knowledge of disturbing activities and do not waste time on switching between project activities and disturbing activities. The engineer(s) that also perform(s) disturbing activities will have slack time in their planning to perform these disturbing activities and work the rest of his time on project activities. (Section 2.2) When we have one engineer that performs all the disturbing activities, we exclude the random selection of an engineer that we used in the standard scenario.

5.1.4 Intervention II - Dedicated engineer for disturbing activities

Section 2.2 described that hospitals can decide to make use of a dedicated emergency operating room. We compare this to the use of dedicated engineer that only performs disturbing activities (and no project activities at all). We replace one engineer by an engineer that only performs disturbing activities. The other engineers do only perform project activities.

5.1.5 Intervention III – Work in overtime

By allowing engineers to work in overtime, we try to reduce the throughput time of projects and the number of projects that is completed too late. We simulate scenarios were all engineers are allowed to work 4 / 8 hours in overtime per week. All other parameters are the same compared to the standard scenario.

5.1.6 Intervention IV - Priorities of disturbing activities

Section 2.2 described how prioritizing emergencies result in less disturbances in a planning. When disturbing activities have a priority, this means that not every disturbing activity must be performed immediately. Instead, it can wait until an engineer or programmer has finished

a planned project activity, or directly at the beginning of a workday / after the break. Potentially, this can result in less switching moments and switching time. Figure 5.1 shows an example of this concept. When no disturbing activities occur, an engineer only has a switching moment at the beginning of a day and directly after the break. When there occur 3 disturbing activities that this engineer has to perform directly, this results in 6 extra switching moments. When he does not have to perform these disturbances directly, because they don't have such a high priority, this results in a decrease of switching moments.
Since we do not know what the true ratio between disturbing activities with a high and low priority is, we simulate 2 different scenarios:

- 50% low priority / 50% high priority
- 80% low priority / 20% high priority

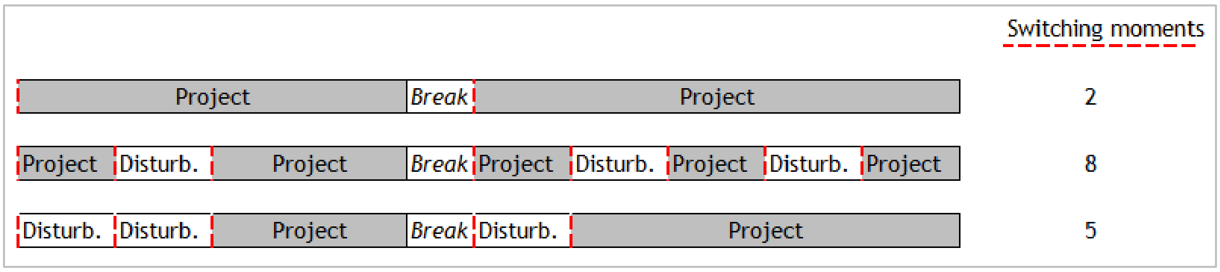

Figure 5.1 Example reduction of switching moments

5.2 Results

This section shows the numerical results of the standard scenario and the scenarios that we described in the previous section.

5.2.1 Standard scenario

Throughput times & work ratios engineers

We analyzed 25 runs of the projects A and B in the standard scenario. Table 5.1 shows the working ratios of the 3 engineers and the total throughput time of the 25 runs.

	Competencies			
	Project activities	**Disturbing activities**	**Working ratio**	**THP (days)**
Engineer 1	✓	✓	94%	2111
Engineer 2	✓	✓	93%	
Engineer 3	✓	✓	86%	

Table 5.1 Throughput time & working ratio engineers standard scenario

We see that all the engineers are working for around 90% of their time on a project or disturbing activity. The other time is wasted due to switching and waiting times. The total throughput time of the 25 runs is 2111 days. Since the selection of an engineer for a disturbing activity is random, we expected that the working ratios of all the three engineers would be equal. However, we see that the working ratio of Engineer 3 is lower than the working ratio of Engineer 1 and 2. This is due to simulation software that picked Engineer 3 in cases that all the engineers were available or were all performing project activities.

Switching moments

Switching moments are directly related to the occurrence of disturbing activities. When a disturbing activity occurs, an engineer immediately has to stop its current activity. Every disturbing activity results in two extra switching moments, compared to a normal working day without any disturbing activities. (Figure 5.2)

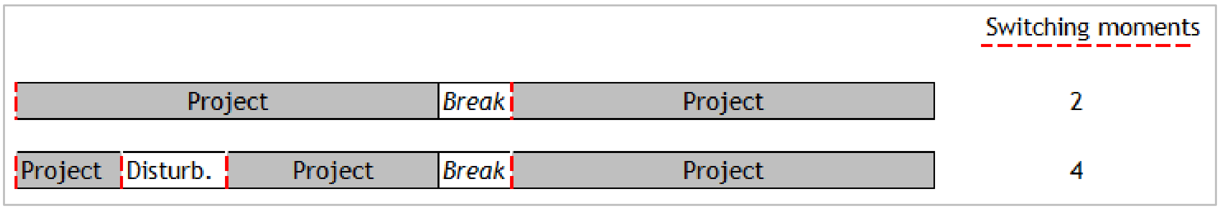

Figure 5.2 Relation between disturbing activities and switching moments

We assume that disturbing activities always result in two extra switching moments, that they do never occur directly after a break or at the beginning of the working day. We also neglect the switching moments between two different project activities. Table 5.2 shows the number of disturbing activities and switching moments during 25 runs of the standard scenario.

Days	2111
Number of engineers	3
Standard switching moments / day	2
Total standard switching moments	12666
Disturbing activities	3554
Switching moments / dist. activity	2
Total switching moments disturb.	7108

Table 5.2 Disturbing activities & switching moments standard scenario

Obviously, we can’t reduce the standard switching moments at the beginning of a working day and at after the break. However, we can reduce the number switching moments caused by disturbing activities. (Section 5.2.5)

Lateness of projects

In the current situation, the probability that a project will not be completed before the agreed deadline is very high. (Figure 5.3)

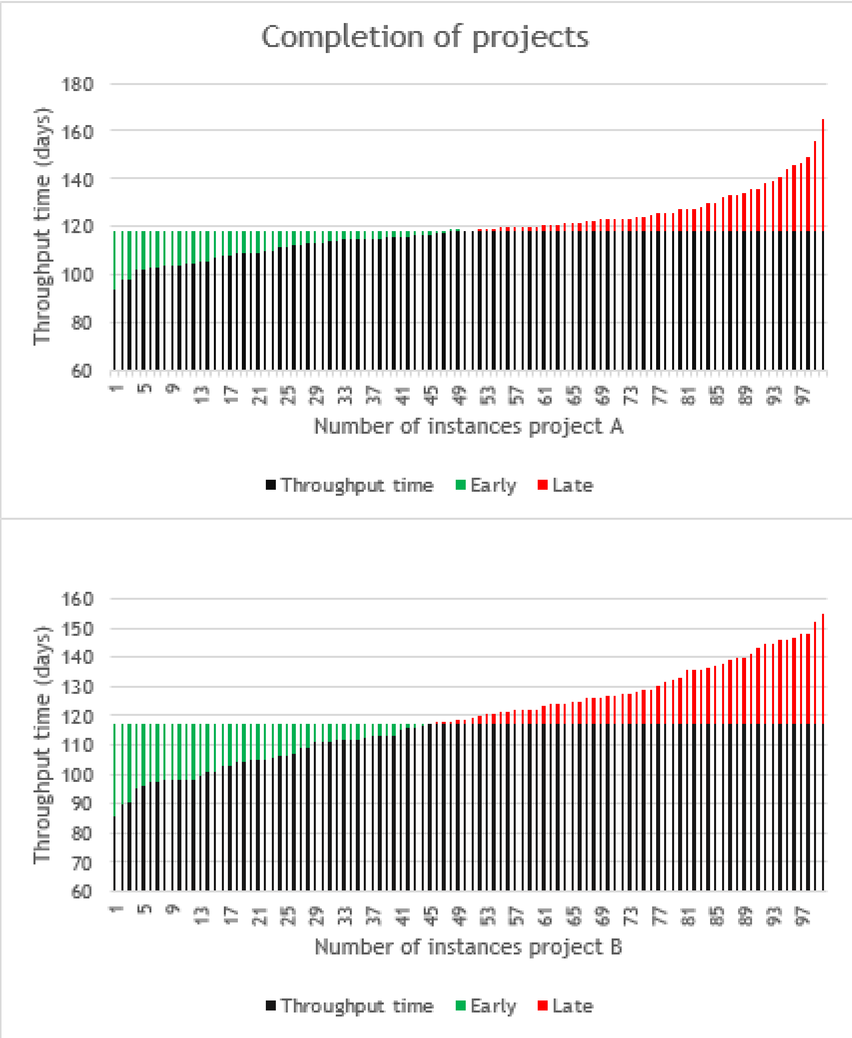

Figure 5.3 Completion of projects standard scenario

Table 5.3 shows the lateness of the simulated projects. We conclude that the probability that a project is delivered after the agreed deadline is around 50%. The average lateness of these projects is more than 10 days towards the throughput time of a project.

Project	% projects exceeding deadline	Avg. lateness
A	49%	11 days
B	55%	14 days

Table 5.3 Lateness of projects standard scenario

5.2.2 Intervention I - Competences of engineers

Throughput times & work ratios engineers

We analyzed 25 runs of the projects A and B in different compositions of engineers. (Table 5.4) The total of engineers is 3, the minimum number of engineers that can perform disturbing activities is 1. We conclude that the differences in both throughput time and working ratio do not differ significantly between the simulated configurations. The throughput time of the scenario with 1 engineer that only performs project activities has been reduced with 4% compared to the standard scenario.

	Competencies			
	Project activities	**Disturbing activities**	**Working ratio**	**THP (days)**
Engineer 1	✓	✓	88%	
Engineer 2	✓	✓	93%	2035
Engineer 3	✓	✗	95%	

	Competencies			
	Project activities	**Disturbing activities**	**Working ratio**	**THP (days)**
Engineer 1	✓	✓	88%	
Engineer 2	✓	✗	94%	2063
Engineer 3	✓	✗	92%	

Table 5.4 Throughput time & working ratios with different compositions of engineers

Switching moments

The number of switching moments does not change compared to the standard scenario, since the priorities of disturbing activities do not change in this scenario.

Lateness of projects

When we look at the lateness of projects, we conclude that the results are comparable to the standard scenario. This is in line with the throughput times, that also do not differ from the standard scenario. Table 5.5 shows the results for the scenario where 2 of the 3 engineers can perform disturbing activities, Table 5.6 shows the results for the scenario where only 1 engineer can perform disturbing activities.

Project	**% projects exceeding deadline**	**Avg. lateness**
A	50%	11 days
B	50%	13 days

Table 5.5 Lateness of projects Intervention I-i

Project	**% projects exceeding deadline**	**Avg. lateness**
A	46%	11 days
B	54%	14 days

Table 5.6 Lateness of projects Intervention I-ii

5.2.3 Intervention II - Dedicated engineer for disturbing activities

Throughput times & work ratios engineers

We now choose to bring in a dedicated engineer for disturbing activities. This engineer solves all the disturbing activities and is not allowed to perform project activities. (Table 5.7) This does not lead to a significant improvement in terms of THP and working ratios of engineers. In the case that we replace 1 engineer by a dedicated engineer for disturbing activities, the THP increases by 800 days (38% compared to the standard scenario). The dedicated engineers work for only 38% of his available working time, which makes it not very beneficial to have such an engineer in the team of engineers. When we add 1 dedicated engineer to a team of 3 engineers that only perform project activities, the THP is comparable to the standard scenario, but this is with a total of 4 engineers (instead of 3).

	Competencies			
	Project activities	**Disturbing activities**	**Working ratio**	**THP (days)**
Engineer 1	✓	✗	94%	
Engineer 2	✓	✗	90%	2921
Engineer 3	✗	✓	38%	

	Competencies			
	Project activities	**Disturbing activities**	**Working ratio**	**THP (days)**
Engineer 1	✓	✗	95%	
Engineer 2	✓	✗	91%	2025
Engineer 3	✓	✗	78%	
Engineer 4	✗	✓	39%	

Table 5.7 Throughput time & working ratios with dedicated engineer for disturbing activities

Switching moments

The number of switching moments does not change compared to the standard scenario, since the priorities of disturbing activities do not change in this scenario.

Lateness of projects

We determined the lateness of projects for the scenario with 3 engineers that only perform project activities and 1 dedicated engineer for disturbing activities. The lateness of this scenario is also comparable to the standard scenario. (Table 5.8)

Project	% projects exceeding deadline	Avg. lateness
A	50%	10 days
B	52%	15 days

Table 5.8 Lateness of projects Intervention II

5.2.4 Intervention III - Work in overtime

Throughput times & work ratios engineers

Table 5.9 and Table 5.10 show the throughput times and work ratios of engineers when we allow them to work respectively 4 and 8 hours per week in overtime. As we expected, the throughput times of the project reduces. An important factor for this reduction can be found in the occurrence of disturbing activities outside the standard working hours. The disturbing activities only occur in the standard hours. The engineers can completely focus on projects outside the standard working hours, so the lack of switching time makes these hours more efficient.

	Competencies			
	Project activities	Disturbing activities	Working ratio	THP (days)
Engineer 1	✓	✓	94%	1909
Engineer 2	✓	✓	92%	
Engineer 3	✓	✓	82%	

Table 5.9 Throughput time & working ratios 4 hours overtime

	Competencies			
	Project activities	Disturbing activities	Working ratio	THP (days)
Engineer 1	✓	✓	94%	1703
Engineer 2	✓	✓	93%	
Engineer 3	✓	✓	85%	

Table 5.10 Throughput time & working ratios 8 hours overtime

Switching moments

The number of switching moments does not change compared to the standard scenario, since the priorities of disturbing activities do not change in this scenario.

Lateness of projects

The lateness of the projects is reduced in case we let the engineers make use of overtime. When we allow them to work 8 hours in overtime per week, we reduce the probability that a project is delivered too late from 49% to 2%. (Table 5.11)

Max. overtime	% projects exceeding deadline	Avg. Lateness
4 hours	16%	13 days
8 hours	2%	7 days

Table 5.11 Lateness of projects A when overtime is allowed

5.2.5 Intervention IV - Priorities of disturbing activities

Throughput times & work ratios engineers

Table 5.12 shows the effect on the throughput time of the simulation and the working ratios of the engineers in case that 50% of the disturbing activities has low priority. The THP has reduced to 2025, while the working ratios of engineers are similar to the standard scenario. When 80% of the disturbing activities has low priority, the throughput time reduces to 1979 days, with the same working ratios as shown in Table 5.12.

	Competencies			
	Project activities	**Disturbing activities**	**Working ratio**	**THP (days)**
Engineer 1	✓	✓	94%	2025
Engineer 2	✓	✓	93%	
Engineer 3	✓	✓	87%	

Table 5.12 Throughput time & working ratios prioritized disturbing activities

Switching moments

When we assume that 50% of all the disturbing activities that occur can wait until after the break or the following morning (low priority), we can already achieve a significant reduction of the switching moments that are caused by disturbing activities. (Table 5.13) The reduction in this case is 1777 moments. This is a reduction of 25 percent of switching moments caused by disturbing activities compared to the standard scenario. When 20% of the disturbing activities has low priority, we achieve a reduction of 40% of switching moments due to disturbing activities.

Standard scenario

Days	2111
Number of engineers	3
Standard switching moments / day	2
Total standard switching moments	12666
Disturbing activities	3554
Switching moments / dist. activity	2
Total switching moments disturb.	7108

50% low priority / 50% high priority

Days	2025
Number of engineers	3
Standard switching moments / day	2
Total standard switching moments	12150
Disturbing activities high priority	1777
Switching moments / dist. activity	2
Disturbing activities low priority	1777
Switching moments / dist. activity	1
Total switching moments disturb.	5331

20% low priority / 80% high priority

Days	1979
Number of engineers	3
Standard switching moments / day	2
Total standard switching moments	11874
Disturbing activities high priority	711
Switching moments / dist. activity	2
Disturbing activities low priority	2843
Switching moments / dist. activity	1
Total switching moments disturb.	4265

Table 5.13 Reduction of switching moments

Lateness of projects

When 50% of all the disturbing activities does not have to be performed immediately, the probability that projects are delivered too late reduces. The average lateness of these project also decreases compared to the standard scenario. (Table 5.14) Further reductions are achieve when it appears that only 20% of all disturbing activities has high priority. (Table 5.15)

Project	% projects exceeding deadline	Avg. Lateness
A	43%	10 days
B	54%	11 days

Table 5.14 Lateness of projects prioritized disturbing activities (50% low / 50% high)

Project	% projects exceeding deadline	Avg. Lateness
A	39%	9 days
B	46%	12 days

Table 5.15 Lateness of projects prioritized disturbing activities (80% low / 20% high)

5.3 Conclusions

In this chapter, we presented the numerical results of the simulation model. We started with the results of the standard scenario. The performance of the simulation is presented in terms of:

- Throughput time of projects
- working ratios of the engineers
- Number of switching moments
- Lateness of projects

In this chapter, we were looking for an answer to the following question:

Question 5: How can we change the planning of engineers and programmers at Romias to make it more efficient and more resistant to disturbing activities and variable duration of engineering and programming activities?

To find an answer, we simulated four scenarios in which we changed some input scenarios of the model.

1. Competences of engineers. It is beneficial in term of throughput time to replace one or two engineers that perform both project and disturbing activities by engineers that only perform project activities.
2. Dedicated engineer for disturbing activities. We conclude that it is not beneficial to have such an engineer, because there is not enough work to be done. This engineer would have a work ratio of 38%, which is too low. We therefore prefer a situation where we have two engineers that can perform both project and disturbing activities and one engineer that only performs project activities.
3. Work in overtime. By allowing engineers to work 4 hours per week in overtime, we can already reduce the probability that a project is delivered too late from 49% to 16%. When we allow them to work 8 hours per week in overtime, this percentage reduces to 2%.
4. Priorities of disturbing activities. We found out that the number of switching moments between activities can be reduced by prioritize the disturbing activities. When 50% of the disturbing activities can wait until after the break or the beginning of the next day, the number of switching moments causes by disturbing activities is

reduced by 25%. This also leads to a decrease of the throughput time and the probability that a project is delivered too late.

In the next chapter, we present the conclusions of this research and recommendations for the management of Romias. We also give some advice regarding to potentially further research.

6 Conclusion and recommendations

This chapter describes the conclusion of the research and the forthcoming recommendations for the management of Romias and suggestions for further research. Section 6.1 contains the conclusion of this research. Section 6.2 provides the recommendations for the management of Romias, including further research. Section 6.3 is a discussion in which we reflect on used methods and literature in this research.

6.1 Conclusion

The goal of this research is to get more insight in the planning of staff and to improve it by reducing the number of projects that is delivered too late and the overtime that staff needs to complete projects. We used the following research question:

How can Romias improve the planning of engineers and programmers in such a way that they are able to perform all their tasks within the planned time?

From the literature about planning in Engineer-To-Order environments and planning of operating theaters, we constructed a simulation model to find improvements of the current planning process at Romias. Table 6.1 summarizes the outcomes of the simulation model.

	Input						Output			
	Number of engineers				Allowed overtime (hours)	% Disturbing activities with high priority	Total THP (days)	Switching moments due to dist. act.	% Projects 'A' exceeding deadline	Average lateness projects 'A' (days)
	Project activities	Disturbing activities	Both	Total						
Standard scenario	0	0	3	3	0	100%	2111	7108	49%	11
Intervention 1.1	1	0	2	3	0	100%	2035 (-3,6%)	7108	50% (+2%)	11
Intervention 1.2	2	0	1	3	0	100%	2063 (-2,3%)	7108	46% (-6,1%)	11
Intervention 2	3	1	0	4	0	100%	2025 (-4,1%)	7108	50% (+1%)	10 (-9,1%)
Intervention 3.1	0	0	3	3	4	100%	1909 (-9,6%)	7108	16% (-67,3%)	13 (+18,2%)
Intervention 3.2	0	0	3	3	8	100%	1703 (-19,3%)	7108	2% (-95,9%)	7 (-36,4%)
Intervention 4.1	0	0	3	3	0	50%	2025 (-4,1%)	5331	43 (-12,2%)	10 (-9,1%)
Intervention 4.1	0	0	3	3	0	20%	1979 (-6,3%)	4265	39 (-20,4%)	9 (-18,2%)

Table 6.1 Summary results simulation model

Interventions 3 and 4 give the most promising results. From the results of the simulation model, we draw the following conclusions:

- <u>Reconsider the competencies of engineers</u>
  It is not necessary that every engineer has the competencies to perform both project and disturbing activities. It is better to have one engineer that performs all the disturbing activities. This engineer can work on project activities in the rest of this time, since there are not enough disturbing activities for a full-time job.
- <u>Increase the capacity of engineers</u>
  We conclude that work in overtime reduces the probability that projects are delivered too late, as a result of decreased throughput times (days). By allowing engineers to work 8 hours in overtime per week, we reduce the probability that a project is delivered too late from 49% to 2%. This means that a higher capacity of engineers can lead to a reduction of the throughput times of projects. This does not

necessarily have to be done by allowing engineers to work in overtime. An extra engineer that works part-time or full-time on project activities during standard working hours can also be a good solution.

- Prioritize disturbing activities
  We conclude that prioritizing disturbing activities reduces the number of switching moments between activities. Since every switching moment costs time for an engineer, valuable time will be saved. When 50% of all disturbing activities can wait until the next day / directly after the break, the throughput time of projects reduces with 4%. The probability that projects are delivered too late also reduces. Bigger improvements are made when it appears that only 20% of the disturbing activities has to be performed directly after occurrence.

6.2 Recommendations and further research

From the literature study, the outcomes of the simulation model and the observations that we made in during this research, we can give the management of Romias the following recommendations regarding to the planning of staff:

- Find a way to make it easier for engineers and programmers to register their activities. These data can be used to keep track of the progress of projects. We advise Romias to carry out further research in order to evaluate and select an appropriate software system that can be used to monitor the progress of projects.
- The data about project progress can be used to create a database with project activities and both their estimated and actual duration. When Romias starts a new project, the information in the database can be used to find comparable projects or activities. This should make it easier to make an accurate estimation of activity durations of new Engineer-To-Order projects.
- Make one single person responsible for the planning and the progress of projects. The project manager is the most suitable person to do this. He also should create better fine-tuning between the engineering and software part of projects, since bad coordination between these parts leads to a lot of extra work.
- Make one engineer responsible for the execution of disturbing activities. Other engineers can focus on project activities that do not require all the specific knowledge to perform disturbing activities. Task specifications for the different jobs should be established and used in the selection procedures when new engineers are needed. The same holds for the programmers.
- Prioritize disturbing activities. When a disturbing activity does not have to be performed immediately, a lot of switching moments can be saved. We recommend further research in the nature and priorities of disturbing activities. A clear distinction should be made between disturbing activities that need to be performed immediately and those that can wait a few hours or days. Offering service contracts to customers can be a good option to investigate. The research can mention the assignment of an engineer to a disturbing activity.

6.3 Discussion

This section describes the usability of the methods and literature that we used during this research.

The first step to gain more knowledge about the planning in an Engineer-To-Order environment was the literature study. We already described the limitations of the used literature in section 2.1.4 and section 2.2.6. Literature about planning in the Engineer-To-Order industry is focusing on running one project at a time. The literature about planning of operating theatres is based on more historical data. A lot of operations are performed many times before. The estimated duration and standard deviations can be determined with higher accuracy than those for activities in an ETO project that is never done before. The literature about planning operating theatres in hospitals gave us valuable examples that we used in our simulation model:

- Prioritizing emergencies
- Make use of a dedicated operating room for emergencies

A significant part of the literature about planning of operating rooms is focusing on the clustering of activities with the same variability on a daily basis. This concept is hard to implement in the planning of staff at Romias, since most project activities have a duration that is longer than a day and activities are not repeated, in contract to operations in a hospital.

We continued our research with an analysis of the current planning processes of staff at Romias. We decided to use the framework of Little, Rollins, Peck & Porter (2000) and modified it to analyze the current planning processes at Romias. We encountered a lot of limitations that make it hard to create a planning for a project. (Section 3.2)

To come up with improvements for the planning of engineers, we constructed a simulation model. We used the performance indicators of the planning of operating rooms to determine performance indicators for the model. We already described the limitations of the model itself in Section 0. The outcomes of the standard scenario were comparable to the actual situation. The outcomes of the interventions are measured individually, we did not make combinations of interventions. We assume that a combination of interventions with a positive outcome will also have a positive effect.

A simulation is always a limited representation of the actual system. We therefore could not implement some practical additions that are interesting for Romias' future. We did not consider the smaller projects that Romias performs, as well as the serial production. These projects require a certain amount of engineering capacity as well. However, the durations of activities in serial production is better predictable (less variable) than the activities in ETO projects. A mix of activities for both serial production and ETO projects can make a planning more stable, which results in less projects that are delivered after the agreed deadline.

A simulation model seems to be the right method to test proposed improvements of the planning processes at Romias. However, the model is based on a lot of assumptions that can devaluate the outcomes. A simulation model for the planning of only three engineers feels like it is a little bit too much. Nevertheless, we assume that the tested scenarios will contribute to an improved planning of both engineers and programmers.

Bibliography

Coelli, T., Rao, D., O'Donnell, C., & Battese, G. (2005). *An introduction to efficiency and productivity analysis* (2e ed.). New York: Springer Science.

Cooper, D., & Schindler, P. (2014). *Business Research Methods, 12th edition*. New York: McGraw-Hill.

Dekkers, R. (2006). Engineering management and the Order Entry Point. *International Journal of Production Research, Vol. 44, Nos. 18-19*, 4011-4025.

Evers, J., Oehler, G., & Tucker, M. (1998). Improving engineering productivity: A time study of an engineer's typical work day. *IEEE International Engineering Management Conference*, (pp. 377-383).

Fernandez, A., Armacost, R., & Pet-Edwards, J. (1998). Understanding simulation solutions to resource-constrained project scheduling problems with stochastic task durations. *Engineering Management Journal 10*, 5-13.

Furukawa, Y. (1993). Paradigms for Future Manufacturing Systems. *9th Annual Conference CIM Europe*. Amsterdam.

Goodwin, P., & Wright, G. (2009). *Decision Analysis for Management Judgment*. Chichester: John Wiley & Sons Ltd.

Hans, E., & Vanberkel, P. (2011). Operating Theatre Planning and Scheduling. In R. Hall, *Handbook of Healthcare System Scheduling* (pp. 105-130). Springer.

Hans, E., Herroelen, W., Leus, R., & Wullink, G. (2007). A hierarchical approach to multi-project planning under uncertainty. *Omega - The International Journal of Management Science 35*, 563-577.

Hans, E., van Houdenhove, M., & Hulshof, P. (2011). A framework for Healthcare Planning. In R. Hall, *Patient Flow: Reducting Delay in Healthcare Delivery* (p. Chapter 12).

Hans, E., Wullink, G., Van Houdenhoven, M., & Kazemier, G. (2008). Robust surgery loading. *European Journal of Operational Research 185*, 1038-1050.

Hardesty, D., & Bearden, W. (2004). The use of expert judges in scal development: implications for improving face validity of measures of unobservable constructs. *Journal of Business Research, Vol. 57, Iss. 2*, 98-107.

Herroelen, W., & Leus, R. (2005). Project scheduling under uncertainty: Survey and research potentials. *European Journal of Operational Research 165*, 289-306.

Hicks, C., & Braiden, P. (2000). Computer-aided production management issues in the engineer-to-order production of complex capital goods explored using a simulation approach. *International Journal of Production Research, 38:18*, 4783-4810.

Hopp, W., & Spearman, M. (2008). *Factory Physics*. New York: McGraw-Hill Education.

Klassen, K., Russell, R., & Chrisman, J. (1998). Efficiency and Productivity Measures for High Contact Services. *The Service Industries Journal 18:4*, 1-18.

Larsen, R., & Marx, M. (2012). *An introduction to mathematical statistics and its applications*. Boston: Pearson Education.

Law, A. (2007). *Simulation modeling & analysis*. New-York: McGraw-Hill.

Law, A. (2008). How to build valid and credible simulation models. *Winter Simulation Conference*, (pp. 39-47).

Little, D., Rollins, R., Peck, M., & Porter, J. (2000). Integrated planning and scheduling in the engineer-to-order sector. *International Journal Computer Integrated Manufacturing, Vol. 13, No. 6*, 545-554.

Pandit, A., & Zhu, Y. (2007). An ontology-based approach to support decision-making for the design of ETO (Engineer-To-Order) products. *Automation in Construction 16*, 759-770.

Roland, B., Di Martinelly, C., Riane, F., & Y., P. (2010). Scheduling an operating theatre under human resource constraints. *Computers & Industrial Engineering 58* , 212-220.

Saaty, T. (1990). How to make a decision: The Analytic Hierarchy Process. *European Journal of Operational Research 48*, 9-26.

Safan. (2016). *E-Brake 150-200T ATC*. Retrieved from Website Safan Darley: https://safandarley.com/products/electronic-press-brakes/e-brake-150-200t-atc

Slack, N. (2010). *Operations Management*. Harlow: Pearson Education Limited.

Sommers, M. (2006). *Emergencies in planning and planning emergencies at UMC*. Enschede: University of Twente - Faculty of Behavioral, Management and Socials Sciences.

Stoop, P., & Wiers, V. (1996). The complexity of scheduling in practice. *International Journal of Operations & Production Management, Vol. 16, Iss. 10*, 37-53.

Van Houdenhoven, M., Hans, E., Klein, J., Wullink, G., & Kazemier, G. (2007). A Norm Utilisation for Scarce Hospital Resources: Evidence from Operating Rooms in a Dutch University Hospital. *J Med Syst 31*, 231-236.

Vargas, L. (1990). An overview of the Analytic Hierarchy Process and its applications. *European Journal of Operations Research 48*, 2-8.

Wullink, G., Hans, E., & Leus, R. (2004). *A hierarchical approach to multi-project planning under uncertainty*. Enschede: BETA: Research School for Operations Management and Logistics.

Wullink, G., Van Houdenhove, M., Hans, E., Van Oostrum, J., Van der Lans, M., & Kazemier, G. (2007). Closing Emergency Operating Rooms Improves Efficiency. *Journal of Medical Systems, Vol. 31, Iss. 6*, 543-645.

Appendices

A. Explanation activity types at Romias

Serial production

Romias builds ATC-systems for Safan Darley in series. The improvement of the software for these systems is a continuous process, while engineering activities are very limited and only needed in case of a mechanical improvement of the system. Once the system is completely developed, the only remaining tasks are the material purchasing and the assembly of the systems.

The duration of these activities can be estimated accurately, since these tasks are repeated for every system.

Prototype building

Most of the projects at Romias are one time Engineer-To-Order projects / prototypes. These projects are characterized by an extensive engineering phase and large modifications of the standard software.

The prototypes often contain a lot of new functionalities and/or require integration with new machines. It is therefore hard to estimate the total effort of programming and assembly tasks and to take the forthcoming variation into account.

Disturbing activities

As the name suggests, these activities contain the emergency tasks, like system breakdowns / failures at customer location that require (immediate) action of an engineer / programmer. Also, small tasks like drawings that are needed for an offer and phone calls are part of the disturbing activities. The problem is that most of these activities are not planned. The frequency and duration of the occurrence of these activities is very hard to predict. We assume that these activities occur independent of each other and that their duration is variable. Disturbing activities can be described as all the activities/time that is not spend on planned project activities.

Table A.1 gives an overview of the tasks of engineers and programmers, including the predictability and variability of the task durations.

<table>
<tr><th></th><th>Serial production</th><th>Prototype building</th><th>Disturbing activities</th><th>Slack</th></tr>
<tr><td>Engineers</td><td>• Engineering of the ATC-system for Safan Darley
• Assembly of ATC-system

Easy to predict, low variability</td><td>• Engineering of prototype projects
• Assembly of prototypes

Average to predict, average variability</td><td>• Solving mechanical problems of systems at customer location
• Drawings for project offers
In assembly:
• Clean up
• Searching tools
• Solve errors in customized parts

Hard to predict, high variability</td><td rowspan="2">Buffer time to deal with the uncertainty of (planned) task duration</td></tr>
<tr><td>Programmers</td><td>Improvement of the software for the ATC-system

Easy to predict, average variability</td><td>• Programming of robot movements
• Programming of User Interface
• Integration with machine (Machine Interface

Hard to predict, high variability</td><td>• Solving software / robot issues at customer

Hard to predict, high variability</td></tr>
</table>

Table A.1 Summary of activities Engineers and Programmers

B. Robot systems

Romias builds robot systems that are designed and engineered to order. Customers can use robot systems to automate machines with the following applications:

- Tool Changing
- Milling
- Drilling
- Casting / Moulding
- Storing
- Packaging

Figure B.1 Example standard robot (Fanuc Robotics)

A standard robot (Figure B.1) is used as a basis to perform these operations. The robot is usually equipped with a gripper to grab tools or products. The robot is placed in the robot system (Figure B.2) to perform the desired operations for the customer.

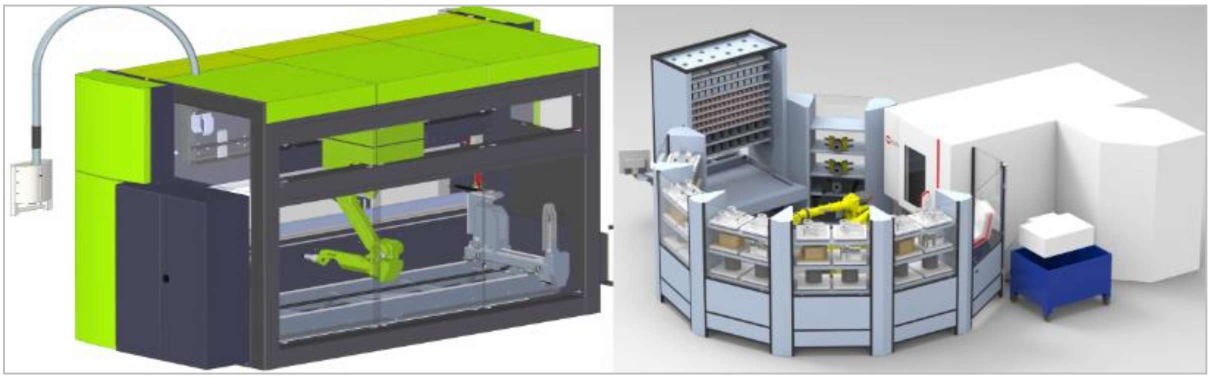

Figure B.2 Examples of robot systems

Some systems contain a warehouse to store tools, finished parts or parts that have to be processed by interacting machines.

C. General process planning

Figure C.1 shows the general process of the current situation at Romias. We will describe the general process based on this figure. This is relevant since engineers and programmers are involved with all these activities.

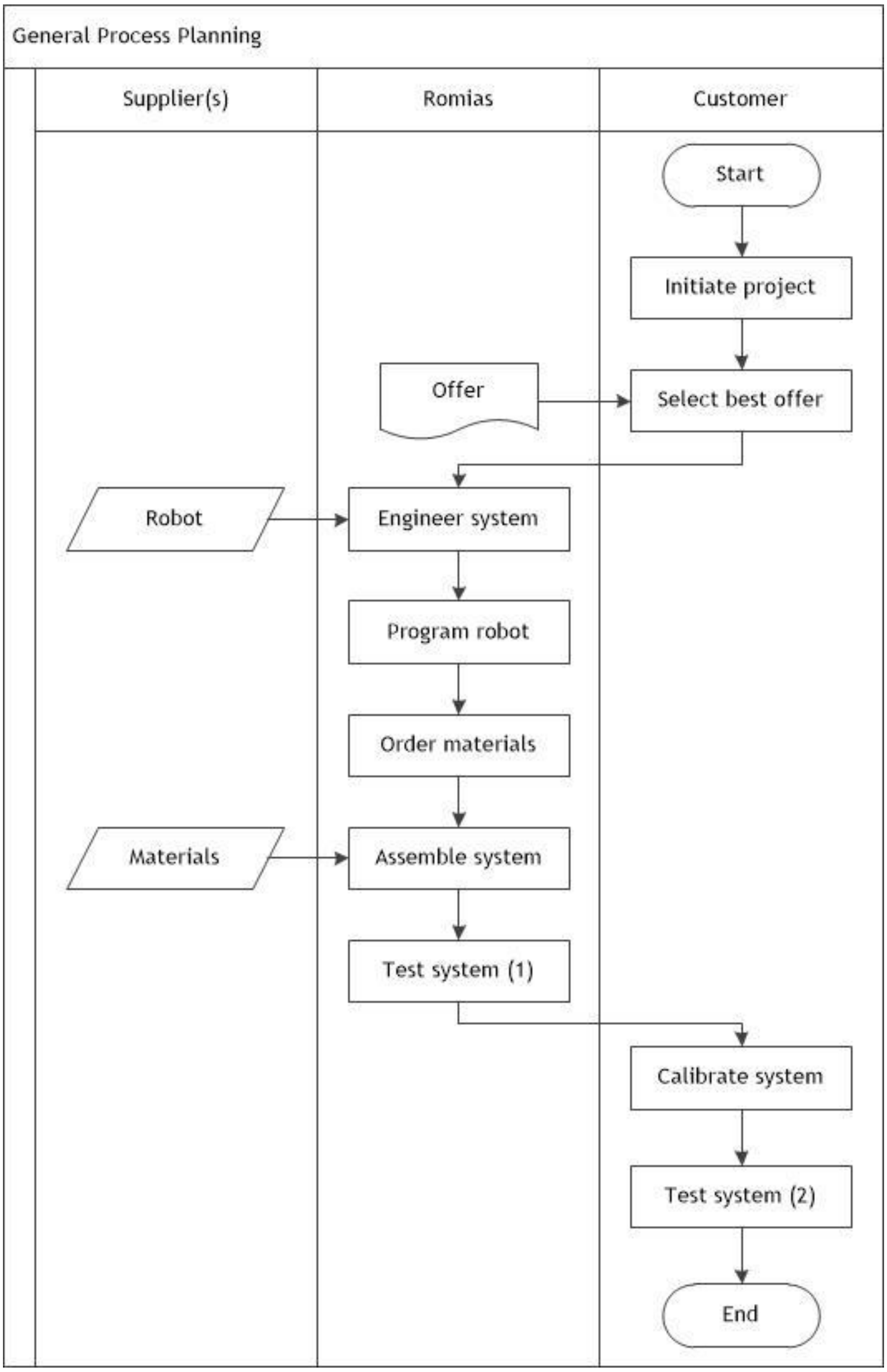

Figure C.1 General process

Table C.1 gives a more detailed example of the planning of a project at Romias, in this case the implementation of ATC on press brakes.

Week	Who	What
1	Romias	Engineering 3D and 2D models of construction and frame
2	Romias	Engineering 3D and 2D models of construction and frame
	Fanuc	Delivers robot at Romias
3	Romias	Masking and spraying at customer location
	Romias	Programming of robot in Roboguide
	ALMI	Production and lead times steel parts
4	ALMI	Production and lead times steel parts
5	Romias	Programming of communication
	ALMI	Production and lead times steel parts
6	Romias	Steel parts finished and assembling of complete construction
	Romias	Programming of communication
	Wila TIPS	Delivers upper clamping
	Romias	Programming of robot movements upper clamping
7	Wila TIPS	Delivers lower clamping
	Romias	Programming of robot communication
	Romias	Testing complete system
8	Romias	Pick up of system and transport to customer
	Customer	Assembling of system and system calibration
	Customer	Testing software and functionality of the system
9	Customer	Testing software and functionality of the system

Table C.1 Example project planning

a. Project tendering

Most of the times, a potential customer contacts Romias to initiate a project. When the management of Romias is interested in the project of the customer, an exploratory meeting is planned to discuss the demands of the customer in general terms.
After the first meeting, some simple renders of the project are made. These renders are based on earlier projects and standard machines. It usually takes around 8 hours to make the renders.

Romias uses the renders for a concept offer. One of the engineers estimates the required amount of time that is needed to engineer the project. The customer receives the concept offer and compares it with the offers of competitors.

Hereafter, Romias makes some more detailed pictures and cost estimations (3 – 4 days work). The customer tries to negotiate lower prices with all the remaining competitors. Romias can reduce its price by dropping some calculated hours, with the risk that a project can't be done in the remaining hours.

b. Engineering and software development

Engineering is one of the first steps in the creation of a robot system. The engineering process starts when Romias wants to make a good offer to a potential customer. Sketches of the system will be made to show the possible result of a robot system. Engineering continues when the customer grants the job to Romias. More detailed specifications are needed in this phase:

- Robot type
- Weight of materials to be handled
- Dimensions
- Number and size of positions in warehouse

The engineers make use of the software Solid Edge to make the 2D and 3D drawings of the system.
The engineers are during a project responsible for:

- Design of the system
- Drawings of the system (2D and 3D)
- Drawings of all required parts
- Calculations of finite elements and payloads
- Electrical schemes
- Purchasing of all required materials

The software part consists of two parts:

- The movement of the robot itself. Every possible position of the robot arm has to be programmed. The same holds for the gripper.
- Design of the user interface (UI). The UI is used by the operators of a customer to set up the machine and needs to be user friendly.

Since (almost) every project is a new Engineer-To-Order project, engineers and software developers always face new properties/functionalities that have to be developed. Some projects are more challenging than others. This means that parts of developed software / engineered systems can be copied and reused, but that there is still a major part that is completely new to the engineers and software developers.

c. Ordering of materials

Ordering materials is currently done manually. Most of the materials are customized and are therefore ordered per project. There is a limited set of general parts that is used in multiple projects. Some of these parts (screws for example) are ordered to stock.

All the other parts are ordered when the engineering work is finished. These parts are ordered from 20-25 different suppliers. A purchase order is manually made per supplier. Ordering of customized parts requires extensive communication with involved suppliers to prevent errors/miscommunication about the drawings that Romias send them to make these parts. The lead times of the suppliers vary between multiple days / weeks. This means that after the engineering, it takes several weeks before all the ordered parts are delivered and the assembly process can be started.

d. Assembly process

The assembly process of a robot system consists of a lot of different steps. Since al systems are different, it is difficult to standardize processes. However, in general we can distinguish the following steps:

The systems are assembled by the engineers. Romias makes use of two production halls, with total space for 2 or 3 systems. When all the materials for a system are delivered, these are stored randomly on the area where the system will be assembled. Some systems are built on a frame on wheels to enable transport through and out the assembly hall. This procedure seems to be inefficient because:

- There is no predetermined plan to assemble a robot system;
- A lot of floor space is required, since most of the materials are on pallets;
- Broad aisles are needed to move the systems through the production halls;
- Handling / movement of materials will take a lot of time during the assembly process;
- Assembly process is expensive, since its completely done by the engineers.

The importance of an efficient assembly process is illustrated by the distribution of costs of a robot system. (Figure C.2)

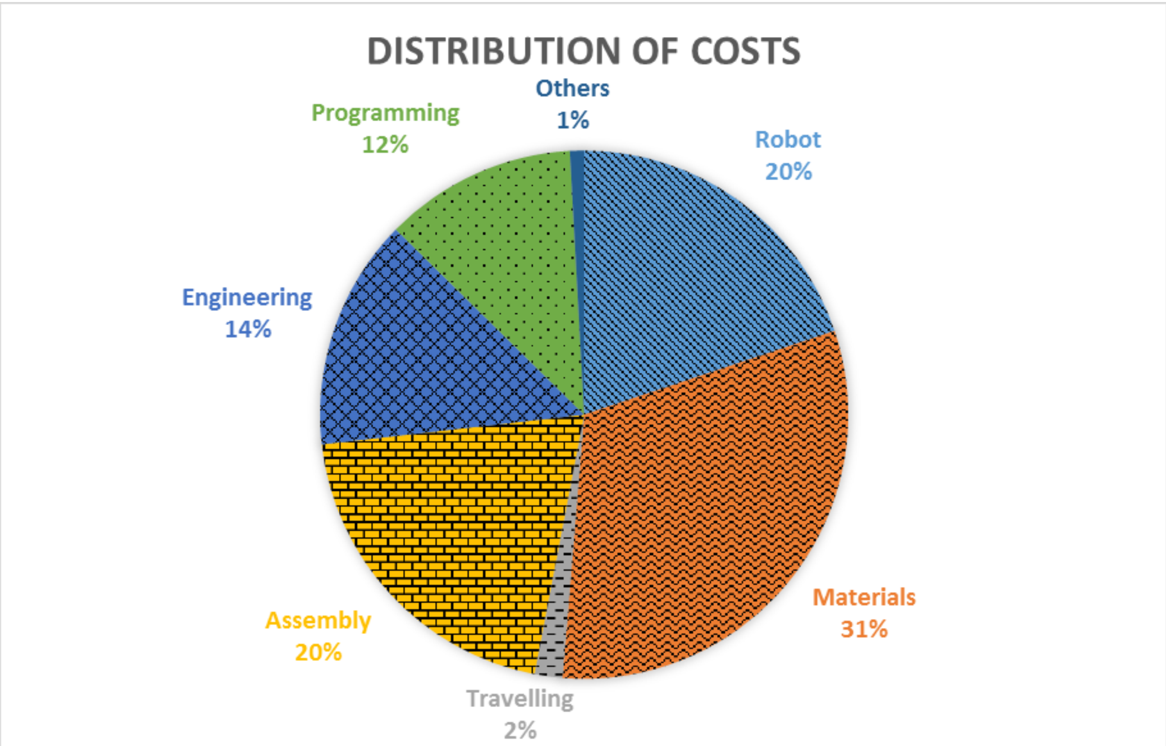

Figure C.2 Distribution of costs

We used the billings of a recent project at Romias to determine the distribution of the costs. The total costs of this system are about €150.000. The figure shows that the robot and other materials represent 51% of the total costs of a system. The other half consists mainly of assembly, engineering and programming costs. The assembly process is performed by the engineers and the costs of the assembly are expressed in labor costs.

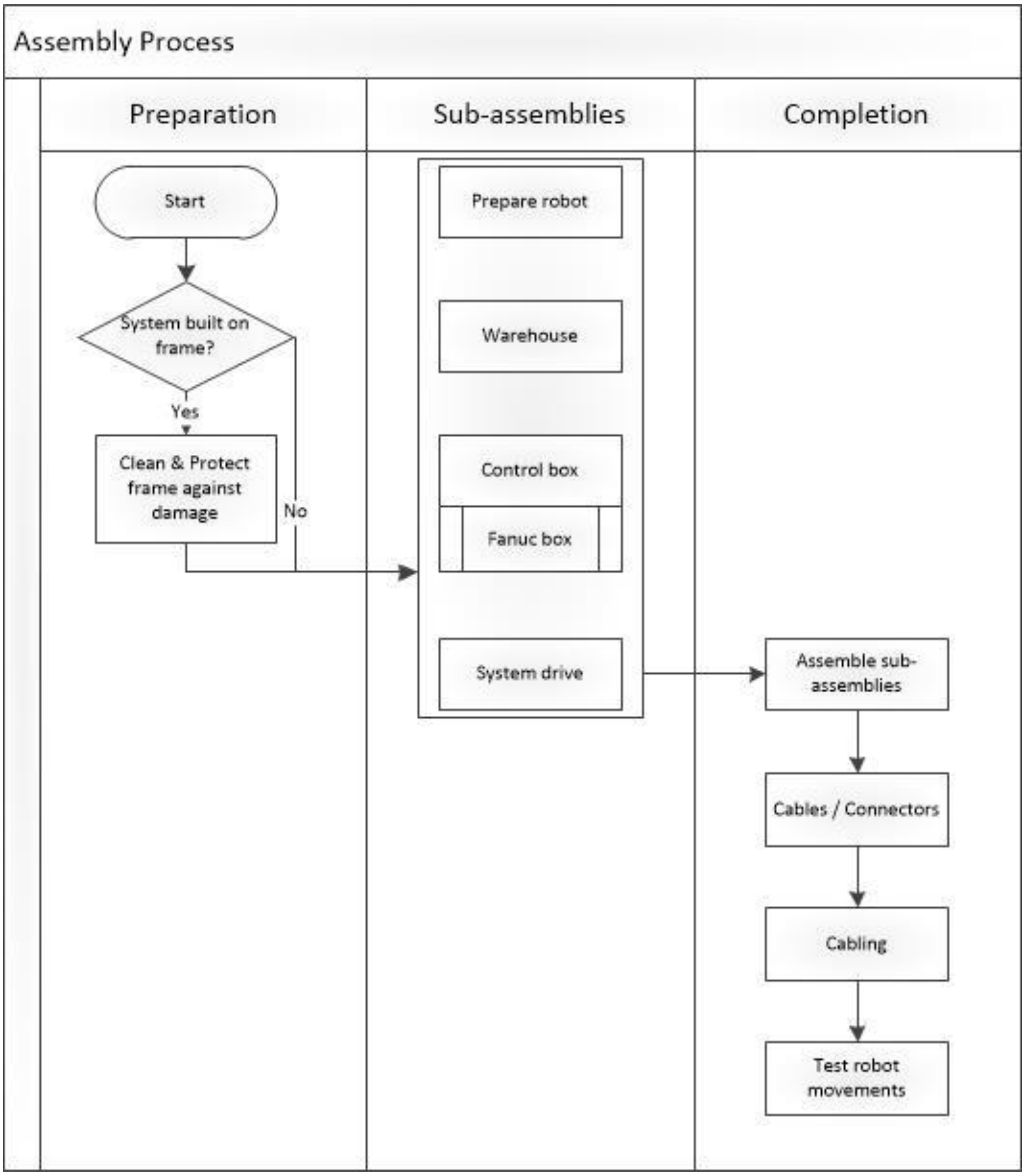

Figure C.3 Assembly process

e. Testing

When the assembly of the system is finished, it can be tested. The testing procedure starts with the calibration of the robot (determining its position). Romias installs the developed software on the system and its functionality will be tested. Sometimes, all the testing is performed at the customer location. This saves duplication of work since calibration of the robot has to be done only at the customer location.

f. Service at customer

In cases that a part of the testing procedure has already been done at Romias, a system has to be (partly) disassembled to prepare it for transport to the customer. When the system is not tested at Romias, the assembly process stops when the system is almost finished and ready for transport. In general, the system consists of a few subassemblies that can easily be assembled when the systems are arrived at the customer location.

D. Weekly planning of engineers and programmers

							Mei																								
		Week 17					Week 18					Week 19					Week 20					Week 21					Week 22				
		M	D	W	D	V	M	D	W	D	V	M	D	W	D	V	M	D	W	D	V	M	D	W	D	V	M	D	W	D	V
Naam	Functie																														
Sebastiaan	Senior WTB Engineer	62	62	62	V	V	19	R	51	51	R	51	1	20	D	R	46	46	46	46	R	46	46	46	46	R	46	46	46	46	R
Detacheerder	Senior WTB Engineer																										1	1	1	1	R
Rob Franke	Senior WTB Engineer																														
Detacheerder	WTB monteur																														
Marc Koershuis	WTB monteur																														
Martijn																															
Bas	Junior WTB Engineer	A	A	A	V	V	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	V	V	A	A	A	A	A
Bob	Senior EL engineer	59	59	78	V	19	78	19	C	78	R	C	C	C	C	C	C	C	C	C	C	47	47	V	V	V	V	47	47	55	R
Efraïm	Junior EL engineer				V					V		V																			
Paul	Senior programmeur	59	59	78	78	V	59	59	C	78	V	C	C	C	C	V	C	C	C	C	V	59	59	78	78	V	59	59	78	78	V
Jeroen	Junior programmeur	19	19	19	19	19	19	19	C	19	19	19	19	19	19	19	19	19	19	19	19										
Bart	Junior programmeur				V	V			C																V	V					

Vrij	V
Cursus	C
Regelcapaciteit	R
Afstudeeropdracht Grijper	A
Diversen	D
Beschikbaar	B

Figure D.1 Weekly planning engineers and programmers

The numbers represent the projects that staff is working during the corresponding weeks/days.

E. Example of offer calculation

Onderdeel:	Type	Bestelnummer:	Leverancier:	Aantal stuks:	Aantal uren:	Risicofactor (1,2,4,10)	Totaal uren met factor:	Inkoop per stuk:	Totaal Inkoop:	Verkoop per stuk:	Totaal verkoop	Levertijd	Uurtarief
				343 Onderdelen			1033 uur	€ 135,704.26	€ 116,905.96	€ 160,550.33	€ 138,751.58	0	
Robot incl wisseldeel, kabelkanon en drukregeling													
Engineering:							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch
Robotsokkel, vlakke vloerplaat			Romias		1	1	1		€ 0.00	€ 0.00	€ 0.00		Mechanisch
Ankerberekening, maku project kopieren			Romias		1	1	1		€ 0.00	€ 0.00	€ 0.00		Mechanisch
Frame robotbesturingskast (zit bij magzijn grijpers in)							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch
IGUS kabelkanon aanpassen naar R2000-**iC en zijkant**					3	1	3		€ 0.00	€ 0.00	€ 0.00		Mechanisch
							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch
							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch
							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch
Materialen:							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch
Robot	R2000iC/165F		Fanuc	1			0	€ 45,800.00	€ 45,800.00	€ 52,670.00	€ 52,670.00		Mechanisch
Robotsokkel, vlakke vloerplaat			Keizersmetaal	1			0	€ 800.00	€ 800.00	€ 1,000.00	€ 1,000.00		Mechanisch
Frame robotbesturingskast (zit bij magzijn grijpers in)							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch
Ethercat	Fanuc		Fanuc	1			0	€ 1,000.00	€ 1,000.00	€ 1,250.00	€ 1,250.00		Mechanisch
Typeplaatje en labels			Letterlicht	1			0	€ 50.00	€ 50.00	€ 62.50	€ 62.50		Mechanisch
Belettering			Letterlicht	2			0	€ 40.00	€ 80.00	€ 50.00	€ 100.00		Mechanisch
Chemische ankers bij klant	Hilti		Hilti	1			0	€ 135.00	€ 135.00	€ 168.75	€ 168.75		Mechanisch
Verwijderbare ankers bij Romias	Hilti		Hilti	1			0	€ 135.00	€ 135.00	€ 168.75	€ 168.75		Mechanisch
Kabelgoot	Keizersmetaal		Keizersmetaal	1			0	€ 500.00	€ 500.00	€ 625.00	€ 625.00		Mechanisch
Luchtverzorgingsunit met druksensor	Festo		Festo	1			0	€ 250.00	€ 250.00	€ 312.50	€ 312.50		Mechanisch
Schunk SWK 110 grijperwisseldeel robot incl aantrekcontrole en E-Module en kabel en stecker				1			0	€ 3,411.00	€ 3,411.00	€ 4,263.75	€ 4,263.75		Mechanisch
IGUS kabelkanon				1			0	€ 2,200.00	€ 2,200.00	€ 2,750.00	€ 2,750.00		Mechanisch
Proportionele ventielen met kabels				2			0	€ 335.00	€ 670.00	€ 418.75	€ 837.50		Mechanisch
Ventielen grijpers en + kabels				3			0	€ 55.00	€ 165.00	€ 68.75	€ 206.25		Mechanisch
							0		€ 0.00	€ 0.00	€ 0.00		Mechanisch

	Inkoop			Verkoop			
Onderdeel:	**Loon kosten:**	Totaal Inkoop:	**Totaal kosten:**	**Uren verkoop:**	**Totaal verkoop:**	**Totaal:**	**Berekend in offerte**
	€ 52,665.66	€ 116,465.26	€ 169,130.92	€ 83,961.25	€ 138,751.58	€ 222,712.83	€ 211,508.50
Robot incl wisseldeel, kabelkanon en drukregeling							
Engineering:	€ 0.00	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	
Robotsokkel, vlakke vloerplaat	€ 50.00	€ -	€ 50.00	€ 77.50	€ 0.00	€ 77.50	
Ankerberekening, maku project kopieren	€ 50.00	€ -	€ 50.00	€ 77.50	€ 0.00	€ 77.50	
Frame robotbesturingskast (zit bij magzijn grijpers in)	€ 0.00	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	
IGUS kabelkanon aanpassen naar R2000-**iC en zijkant**	€ 150.00	€ -	€ 150.00	€ 232.50	€ 0.00	€ 232.50	
	€ 0.00	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	
	€ 0.00	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	
	€ 0.00	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	
Materialen:	€ 0.00	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	
Robot	€ 0.00	€ 45,800.00	€ 45,800.00	€ 0.00	€ 52,670.00	€ 52,670.00	
Robotsokkel, vlakke vloerplaat	€ 0.00	€ 800.00	€ 800.00	€ 0.00	€ 1,000.00	€ 1,000.00	
Frame robotbesturingskast (zit bij magzijn grijpers in)	€ 0.00	€ -	€ 0.00	€ 0.00	€ 0.00	€ 0.00	
Ethercat	€ 0.00	€ 1,000.00	€ 1,000.00	€ 0.00	€ 1,250.00	€ 1,250.00	
Typeplaatje en labels	€ 0.00	€ 50.00	€ 50.00	€ 0.00	€ 62.50	€ 62.50	
Belettering	€ 0.00	€ 80.00	€ 80.00	€ 0.00	€ 100.00	€ 100.00	
Chemische ankers bij klant	€ 0.00	€ 135.00	€ 135.00	€ 0.00	€ 168.75	€ 168.75	
Verwijderbare ankers bij Romias	€ 0.00	€ 135.00	€ 135.00	€ 0.00	€ 168.75	€ 168.75	
Kabelgoot	€ 0.00	€ 500.00	€ 500.00	€ 0.00	€ 625.00	€ 625.00	
Luchtverzorgingsunit met druksensor	€ 0.00	€ 250.00	€ 250.00	€ 0.00	€ 312.50	€ 312.50	
Schunk SWK 110 grijperwisseldeel robot incl aantrekcontrole en E-Module en kabel en stecker	€ 0.00	€ 3,411.00	€ 3,411.00	€ 0.00	€ 4,263.75	€ 4,263.75	
IGUS kabelkanon	€ 0.00	€ 2,200.00	€ 2,200.00	€ 0.00	€ 2,750.00	€ 2,750.00	
Proportionele ventielen met kabels	€ 0.00	€ 670.00	€ 670.00	€ 0.00	€ 837.50	€ 837.50	
Ventielen grijpers en + kabels	€ 0.00	€ 165.00	€ 165.00	€ 0.00	€ 206.25	€ 206.25	

Table E.0.1 Example offer calculation

F. Probabilities of combined frequency/duration disturbing activities

Frequency/duration (min.)		10	30	60	120	180	240	460
		0.514403292	0.308642	0.102881	0.05144	0.015432	0.005144	0.002058
0	0.028901734	0.014867147	0.00892	0.002973	0.001487	0.000446	0.000149	5.95E-05
1	0.115606936	0.059468589	0.035681	0.011894	0.005947	0.001784	0.000595	0.000238
2	0.173410405	0.089202883	0.053522	0.017841	0.00892	0.002676	0.000892	0.000357
3	0.289017341	0.148671472	0.089203	0.029734	0.014867	0.00446	0.001487	0.000595
4	0.202312139	0.10407003	0.062442	0.020814	0.010407	0.003122	0.001041	0.000416
5	0.144508671	0.074335736	0.044601	0.014867	0.007434	0.00223	0.000743	0.000297
6	0.028901734	0.014867147	0.00892	0.002973	0.001487	0.000446	0.000149	5.95E-05
7	0.014450867	0.007433574	0.00446	0.001487	0.000743	0.000223	7.43E-05	2.97E-05
8	0.002890173	0.001486715	0.000892	0.000297	0.000149	4.46E-05	1.49E-05	5.95E-06

Table F.1 Probabilities of combined frequency/duration disturbing activities

G. Projects and expected duration simulation model

Project A		Project B	
Engineering activity	**Duration (hours)**	**Engineering activity**	**Duration (hours)**
Layout	80	Layout	80
Warehouse_Product	64	VLS	36
Spoelunit	64	Servo	80
Servo grijper	80	Afscherming	40
Warehouse_Pallet	40	Assembly	240
Afscherming	40		
Assembly	164		

Durations are expected durations without applied risk factor

Table G.1 Projects and expected duration simulation model

H. Variability of project activities

Since every ETO project is only performed once, we can make use of historical data to compare multiple activity durations of the same project. We therefore assume that the duration of project activities is normally distributed. We multiply the duration of each project activity with a random variable between 0,85 and 2. We used the normal distribution with an average of 3 and a standard deviation of 2. The values are divided by 3. Figure I.1 shows the result.

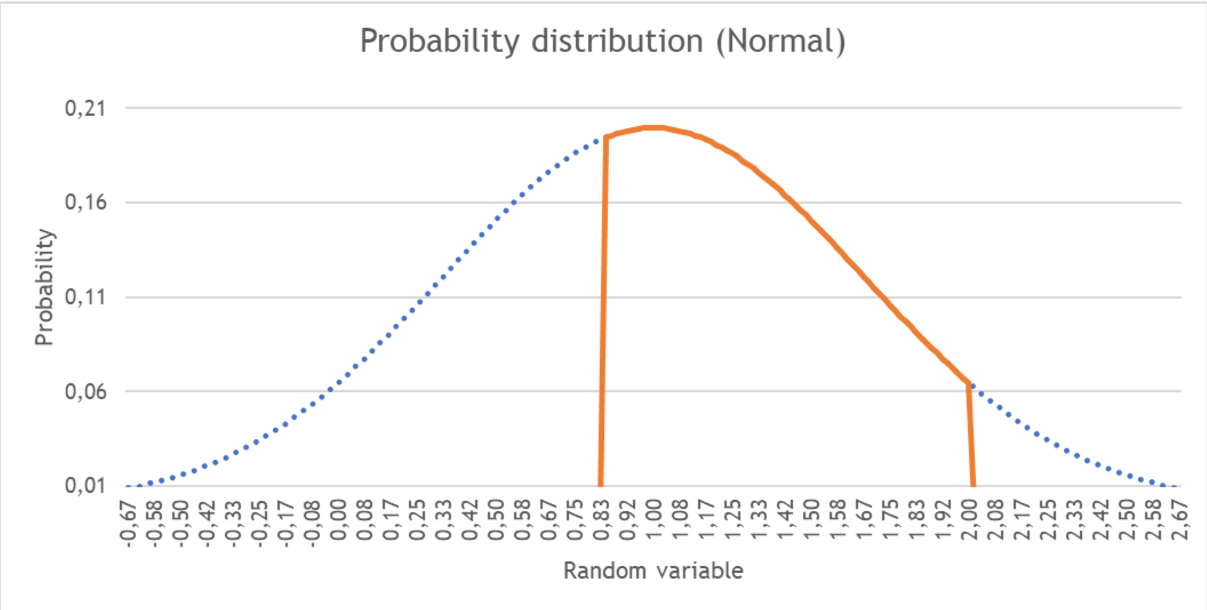

Figure H.1 Probability distribution (Normal) for variable duration project activities

I. Description of programmed model

This section describes the working of the simulation in more detail. We used *Plant Simulation* to build the model. Figure I.1 shows the main frame of the simulation model. We explain the model step by step.

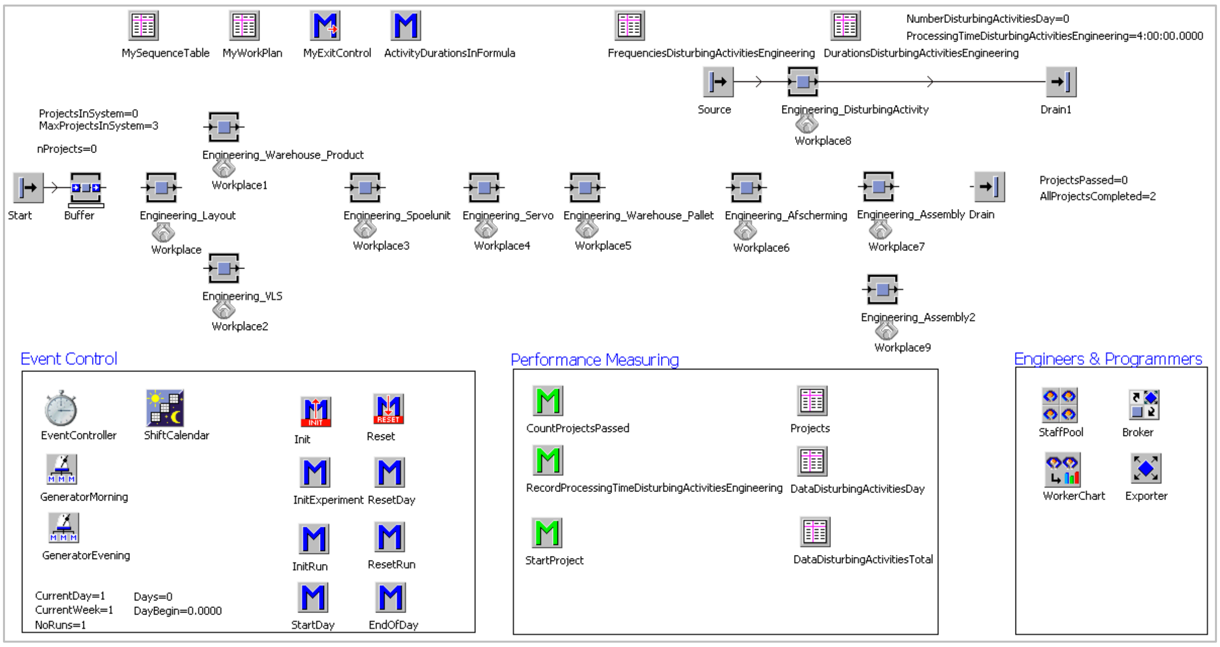

Figure I.1 Main frame simulation model

We start with the tables *MySequenceTable* and *MyWorkPlan*, and the methods *MyExitControl* and *ActivityDurationsInFormula*. A method contains programming code that can be used to give machines orders or to process information from/to tables for example.

Figure I.2 Simulation model I

- The table *MyWorkPlan* contains information about the projects to be executed and the corresponding activities. The table itself contains the projects. Each project has a sub-table that contains all the (engineering) activities that have to be performed by the engineers and the corresponding expected durations.
- *MySequenceTable* keeps track of the current status of a project.
- *MyExitControl* determines the next destination of a project, the next engineering or programming activity to be performed, based on the data of *My*
- *ActivityDurationsInFormula* assigns the processing times of activities to the activities, depending on the project. For example: Engineering_Layout for project 1 has another processing time than project 2.

Figure I.3 shows a part of the engineering activities that can be part of a project.

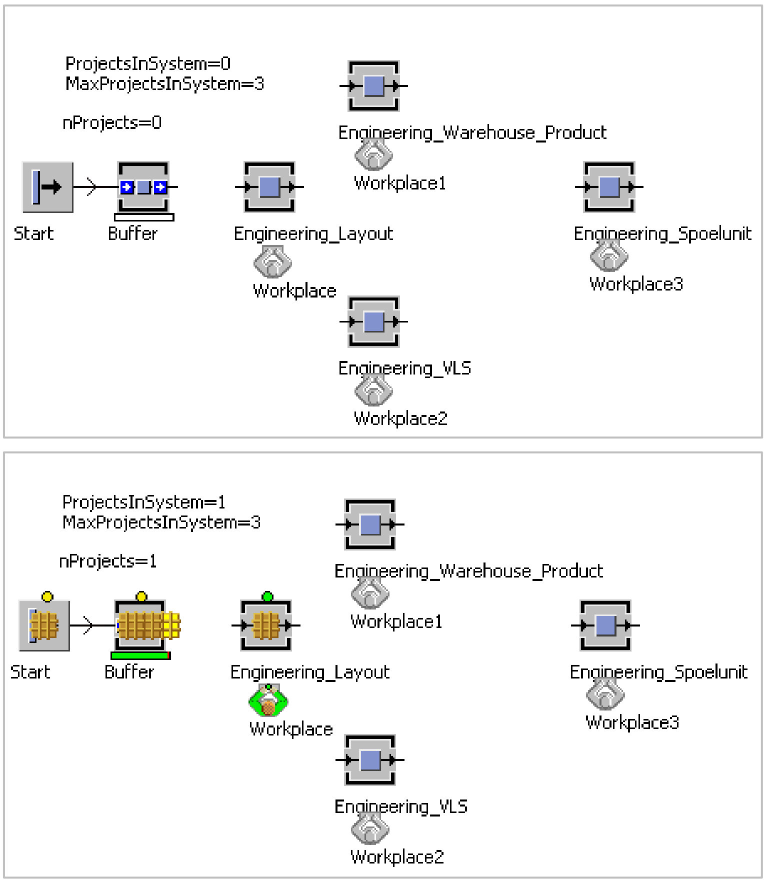

Figure I.3 Simulation model II

- The activities *Engineering_xx* represent all the activities that can be part of the engineering phase of a project. Once an engineering part of a project is created from the table *MyWorkPlan*, the project can start at the first engineering activity. In this case, the first activitiy is *Engineering_Layout*. The sub-tables in *MyWorkPlan* and the method *ActivityDurationInFormula* determine the processing time of the project activity. The method *MyExitControl* sends the project to the next activity.
- A *Buffer* contains projects that have to be performed. These projects enter the system when there a less than the maximum number of projects in the system. The time in the buffer is not included in the processing time / throughput time of the project.
- A *Workplace* is placed near every activity. The *Workplace* is connected to the activity and has place for one *Worker*. A worker with the right competences comes to the workplace and works on the project activity. Every worker has its own competences. Engineers have the competence to perform engineering activities and can also have additional competences like the ability to perform certain disturbing activities.

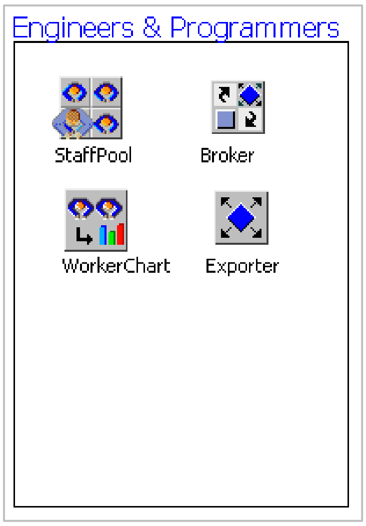

Figure I.4 Simulation model III

The *Workers* are placed in the *StaffPool*. The *StaffPool* contains a list with all the different staff members and the total amount of that type of worker. The *Broker* connects the *StaffPool* to the *WorkPlaces/Activities*. Every time an engineer is needed for a project or disturbing activity, a request is sent to the broker. The *WorkerChart* displays the work ratios of the staff members.

Disturbing activities

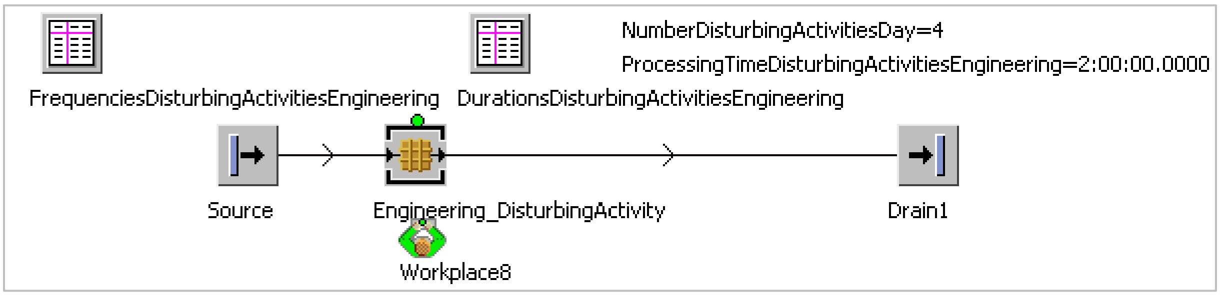

Figure I.5 Simulation model IV

The disturbing activities are programmed as an activity with higher priority than the project activities. Project activities are interruptible, so an engineer can interrupt his project activity to first perform the disturbing activity. The tables include the frequency and duration probability of the disturbing activities. The disturbing activities have to be performed by an engineer that has the competence to perform disturbing activities. When the disturbing activity is performed, it is removed. We keep track of the duration and frequency of disturbing activities per day for the analysis afterwards.

Switching moments

The *Broker* receives a request on every moment that a project activity or disturbing activity has to be performed (or continued). Every request represents a moment that an engineer switches from activity. We use these data to determine the switching moments of engineers.

J. Determination number of runs

We determine the number of runs based on the throughput time of project A. We assume that the same results hold for the other projects that are performed by Romias.

We can create an interval for the throughput time of project A. We want to be 95% certain that the true value of the throughput time is within the interval. In other words, if we run 100 instances (projects A), we expect that 95 of these instances have a throughput time that is within the interval.
We choose α (1 – confidence level) = 0,05. We also choose a γ, the allowed relative error. We choose γ = 0,05.

The interval that we use is:

$$\bar{x}(n) \pm t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}$$

We execute *n* experiments. X_i is the throughput time of instance *i*. $\bar{x}(n)$ is the average throughput time of instances *i = 1…n*. The right site of the formula ($t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}$) is also known as the error. The relative error is: $\frac{t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}}{\bar{x}}$, also denote by γ (γ=0,05). If we use γ, the actual relative error is at most γ/(1-γ). So we use γ'= 0,05/0,95 = 0,053 to compare to $t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}$. We have a valid number of runs when $t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}$ is smaller than 0,053. We conclude that we need at least 15 runs. We choose to use 25 runs as a minimum to be save and to make sure that we also have a valid minimum for the other projects. (Law A. , 2007)