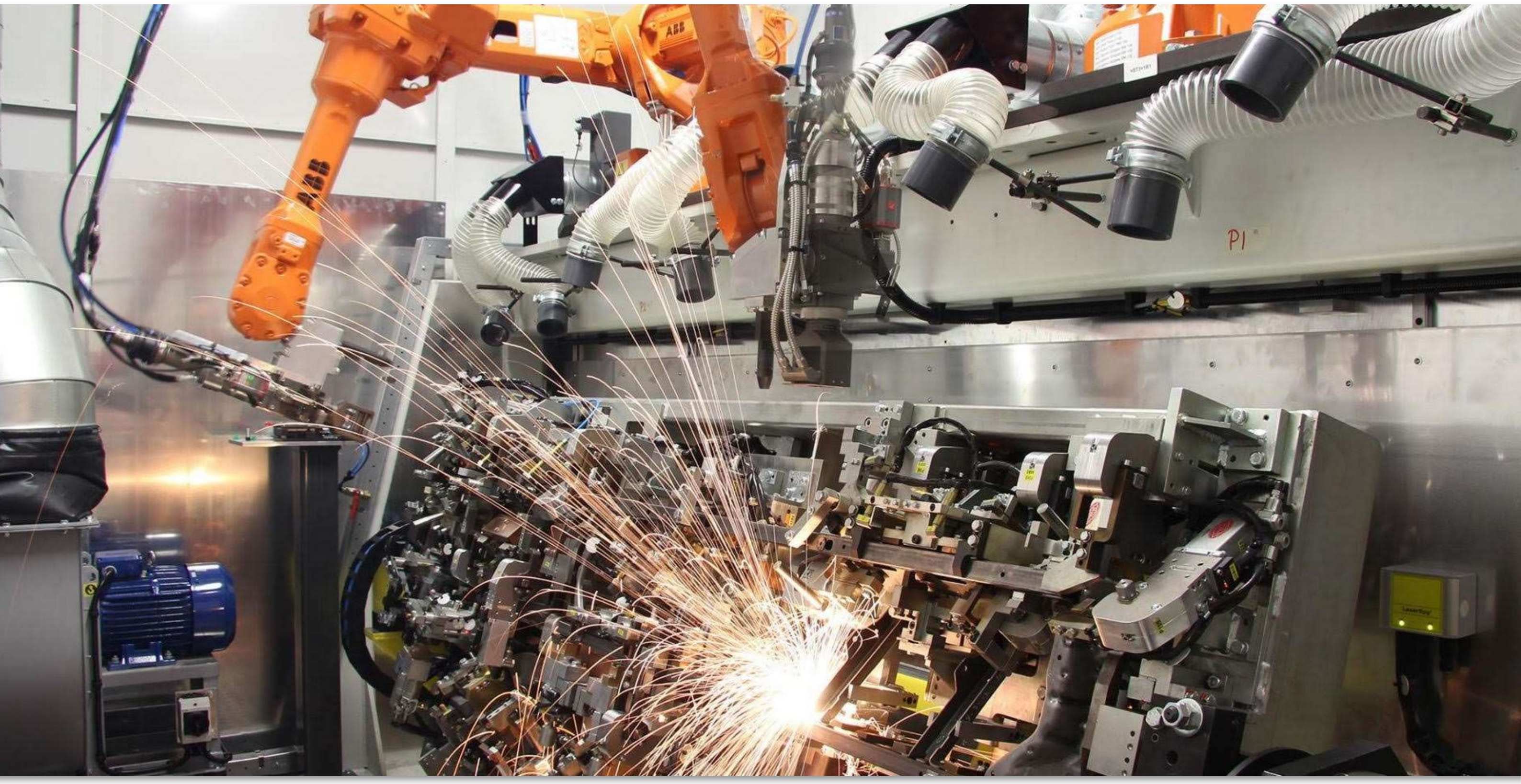
University of Twente

Master Thesis

Redesign of the planning strategy

A case study at AWL-Techniek B.V.



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Preface

This thesis has been written as part of the Master's degree 'Industrial Engineering and Management' with a specialization in 'Production and Logistics Management'. I obviously could not write this thesis on my own, so I would like to thank several persons who were involved during this research.

First of all, I would like to thank Sander Puttenstein for the opportunity to do my thesis at AWL-Techniek B.V. in Harderwijk. Doing this research at a welding company contributed by increasing my practical knowledge. I am thankful for obtaining this practical knowledge which will be useful in my future career. I appreciate the openness and enthusiasm of Sander. The conversations with Sander about our similar interests: playing music and horses, were very pleasant. Furthermore, I would like to thank Joachim Veldkamp for all the explanations regarding the current planning process. The conversations were extremely useful for the progress of my research. His practical knowledge guided me through the planning process. Together we came to interesting insights, which gave me an extra boost for completing this research. Lastly, I would like to thank Johan van Loo for the welding workshop he gave me. It was interesting and super fun to do together. The final result: the barbecue is great.

I also would like to thank my supervisors at the University of Twente, Marco Schutten and Erwin Hans for their supervision, brainstorm sessions with new ideas and feedback. Their passion and enthusiasm about the subject gave me extra energy. The critical and extensive feedback of Marco brought this thesis to a higher academic level. He corrected my repetitive mistakes patiently. Together we had fun about the typo's I have made. For example: 'scare resources' or 'directions for the directors'. Without the positivism and multiple helpful ideas of Marco and Erwin I was not able to finish this thesis.

Finally but most importantly to me, I would like to thank my family and loved ones for their great support and motivation during my graduation project. I consider myself as extremely lucky to have all them around me. In particular, I want to thank my parents, Rob and Elmiere, for all the love they give me every day.

Sharon Boogert,

October, 2019

Management Summary

AWL-Techniek B.V. builds state-of-the art welding machines and operates mainly in the automotive industry. AWL-Techniek B.V. is a project-oriented Engineering-To-Order (ETO) organization. This implies that every designed and build machine is a unique project. AWL-Techniek B.V. plans every project individually and executes a capacity check afterwards. This results in planning multiple projects against infinite capacity while capacity is finite in reality. As a result, many ad-hoc operational changes are required. Changing staff allocations and solving arising problems at hand is daily business at AWL-Techniek B.V. Furthermore, internal deadlines, also called milestones, are often not met. On average, only 49 percent of the milestones are completed on time. This is the core problem of our research and results in the following research question:

'How should the planning strategy of AWL- Techniek B.V. be redesigned such that the number of unmet milestones is minimized?'

We conducted a literature review to analyse the problem from a theoretical perspective. We made a state-of-the-art literature review of planning algorithms for ETO organizations, to understand the problem more in-depth. An important contribution to literature is the mathematical modelling of feeding precedence relations, introduced by Kis (2004).

We found out that a clear definition of the tactical planning function: multi-project planning, is required at AWL-Techniek B.V. Furthermore, integration and interaction is of high importance in order to make multi-project planning successful.

To improve the current planning process, we redesigned the hierarchical planning framework and identified missing planning functions. We identified the following absent planning functions:

- Strategic level: the strategic resource planning is absent
    - There is no long-term demand forecast
    - There is no aggregate capacity management function
- Tactical level: a method for multi-project planning and order acceptance is absent
    - AWL-Techniek B.V. accepts as many orders as possible
    - Projects are planned with a capacity check that is executed only afterwards
- Operational level: no central project scheduling tool or process
    - Every detailed schedule is made manually by a project coordinator

We concluded that especially the tactical planning level is poorly addressed. To improve the current situation, we explained in our research what multi-project planning should look like for AWL-Techniek B.V. Implementing multi-project planning brings multiple advantages. The usage of non-regular capacity (in terms of working in overtime, hiring additional staff and outsourcing activities) will decrease. Hence, the costs of non-regular capacity usage decreases. Furthermore, multi-project planning results in a more stable workload and less ad-hoc changes at the operational level.

In order to make multi-project planning successful, different departments and stakeholders of hierarchical planning levels should interact and integrate with each other. We designed a tactical planning meeting that enables the interaction and integration between these different departments and stakeholders of

hierarchical planning levels. We described the required exchange of data, the decisions that could be made based upon the information that becomes available and the progression of this meeting.

The last step of this research was providing a step-by-step implementation plan for multi-project planning. We identified the steps that have to be taken:

- Collect the data that is required as input for multi-project planning
    - For example, distinguish between different project activities and determine the minimum duration of these project activities
- Create awareness and support for this change
- Change the responsibilities of different employees
    - Tactical planners should be responsible for a multi-project view
    - Tactical planners should stay responsible for the project plan during the entire project execution
    - Operational planners should be responsible for detailed project planning and resource allocation
- Change the software support, such that multi-project planning is supported

We investigated the possible improvements that could be made with the existing planning tool: MS Projects. However, MS Projects is not able to plan project activities efficiently against finite capacity. We therefore proposed a tactical planning algorithm that could be used in a planning tool, based upon our state-of-the-art literature review.

Next to our recommendation to implement multi-project planning, we made other recommendations as well:

- Operational scheduling process should be reassessed. The current operational scheduling process results in different detailed schedules made in isolation. The multi-project overview is missing at the operational level of control. We therefore recommend AWL-Techniek B.V. to reassess this scheduling process.
- The consequences of the order acceptance method should be visualized and assessed towards the sales employees. In order to make multi-project planning successful the effects of accepting a new project should be visual. Visualizing the effects of accepting as many orders as possible can contribute in creating awareness and support for implementing a change.
- AWL should consider another reward structure for the sales employees. The current reward structure result in accepting as many orders as possible, since sales employees receive a bonus above their standard salary (see Section 3.5.1).
- Hiring additional staff should be a decision of tactical planners instead of a decision of operational planners. Capacity flexibility is a characteristic of the tactical planning level.
- Do not focus on an operational utilization of 95% or higher and make new agreements about the operational utilization target. Maximization of the utilization leads to no flexibility against variability in the process. This results in maximization of the waiting times.

Contributions to both science and practice can be summarized as follows:

- We provided a redesign of the hierarchical planning framework, based upon a practical case. We distinguished between a tactical *high* level and tactical *low* level.
- Our other contribution to science concerns the interaction and integration of different planning functions and hierarchical planning levels. This is barely addressed in literature and we emphasized this explicitly in this research.
- One of our practical contribution is the clear implementation plan for multi-project planning in which we distinguished different implementation steps.
- Another practical contribution is the proposed way of working with the existing planning tool, MS Projects.

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Abbreviations

ATO	Assemble-to-order
BOM	Bill of Materials
CODP	Customer order decoupling point
CRN	Customer Request Notification
ERP	Enterprise Resource Planning
ETO	Engineering-to-order
FRCCP	Fuzzy Rough-Cut Capacity Problem
FRCPS	Flexible Resource-Constrained Project Scheduling Problem
HPP	Hierarchical Production Planning
ICPA	Incremental Capacity Planning Algorithm
KPI	Key Performance Indicator
LAP	Largest Activity Part
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MPC	Manufacturing Planning and Control
MRP	Manufacturing Resource Planning
MS Projects	Microsoft Projects
MTO	Make-to-order
MTS	Make-to-stock
S&OP	Sales and Operations Planning
SPH	Shadow Price Heuristic
RCCP	Rough Cut Capacity Planning
RCPSP	Resource-Constrained Project Scheduling Problem
RfQ	Request for Quotation
S&OP	Sales and Operations Planning
WBS	Work Breakdown Structure

Chapter 1: Introduction

This thesis is written in the context of completing my Masters degree Industrial Engineering and Management at the University of Twente. This thesis focuses on the redesign of the planning strategy and puts emphasis on the tactical planning level. This chapter introduces the research at AWL-Techniek B.V. in Harderwijk. Section 1.1 introduces the company. Section 1.2 describes the research problem of this thesis. Section 1.3 describes previous research at AWL-Techniek B.V. Section 1.4 explains the research design.

1.1 Introduction of the company

This section introduces the company. It explains the general history and organization. Section 1.1.2 discusses the markets AWL Techniek B.V. is operating in.

1.1.1 History and organization

AWL-Techniek B.V. started in 1993 as a company specialized in spot and arc welding. The headquarters is located in Harderwijk, the Netherlands. The first foreign facility opened in 2006 in the Czech Republic. A couple years later, AWL-Techniek B.V. opened several facilities in foreign countries. These facilities are located in the United Kingdom, China, Mexico and the United States. Figure 1.1 presents the historical timeline of AWL-Techniek B.V. AWL-Techniek B.V. is abbreviated to AWL from hereon.

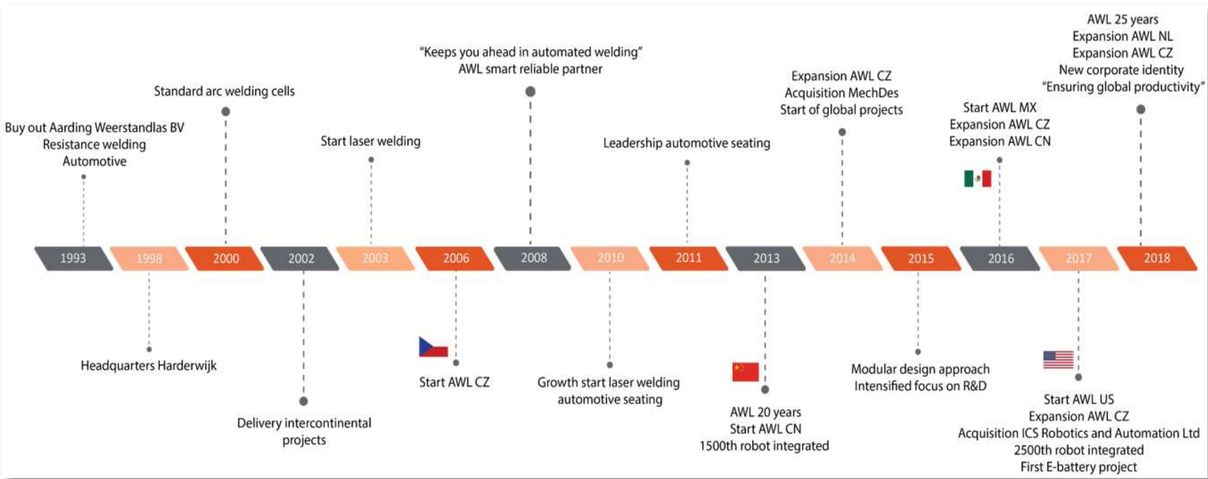

Figure 1.1: Historical timeline of AWL Techniek B.V. (Navision, AWL)

AWL designs, builds and delivers state-of-the art automated welding machines. Different welding processes are used. For example, spot-, arc-, laser- and MAG- welding. The company's internal processes can be divided into physical stages and non-physical stages. Physical stages are manufacturing, assembling and installation activities. Non-physical stages are tendering, designing, engineering and planning. AWL performs physical and non-physical activities herself, but outsources a significant amount of engineering activities to MechDes, a subsidiary of AWL. AWL has 90% percentage of the shares of MechDes.

AWL has 600 employees worldwide and is still expanding every year. AWL employs 435 people in the Netherlands. Other production facilities are smaller; the number of employees varies between approximately 15 and 100 per facility.

In 2018, the revenue of AWL was equal to 116 million euros with an estimated order intake of approximately 140 million euros.

1.1.2 Products of AWL

AWL focuses mainly on two market sectors. The first sector is the automotive industry. This sector generates more than 80% of the total revenue of AWL and can be further divided into the segments: seating, body, Customer Request Notification (CRN) and service. AWL assembles vehicle seating and car body assemblies for the body and seating segment. CRN and service are additional activities requested by customers once the project is already at the customer side.

The second sector is the general industry. The projects built for the general industry are used for warehousing, construction and furniture. These projects are called 'specials'. Figure 1.2 shows the division of the order intake per segment in 2018.

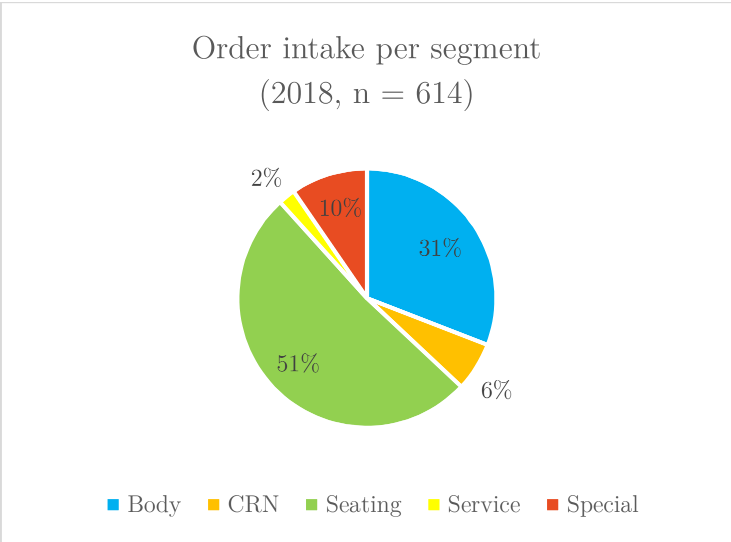

Figure 1.2: Order intake per segment in 2018 (Navision, AWL)

A machine cell produced by AWL is called a project. This means that the entire process to produce a machine cell is part of the project. A project is a unique combination of machines, tools, jigs (moulds for robot machines), software and applications.

1.2 Research motivation

AWL has grown significantly in the recent years and is still growing. The increasing business puts more and more pressure on the existing resources. AWL observes that the current way of planning is unreliable, since milestones are often not met. This results in many ad-hoc changes (e.g. manual adjustments by operational planners) in the plan made and too much non-regular capacity is required to meet the due dates of all projects.

The order intake amount at AWL is uncertain. The sales department tries to sell as many projects as possible. Consequently, order acceptance is not based on the available capacity. A discrepancy between the required capacity for the accepted orders and the actual available capacity is often observed in reality. It is hard to estimate the impact on the capacity at the order acceptance stage because of two reasons:

- Order details are unknown at the order acceptance stage
- An ETO organization must to be able to respond to customer changes throughout the entire process.

This is also the case at AWL and these uncertainties results in the core problem of this research:

'The current planning method results in too many unmet milestones'

The unreliability of the current planning method results in too many unmet milestones. In 2018 only 49% of the milestones were completed in time. Lateness is the difference between the actual finished date of a milestone and the planned finished date of a milestone. The lateness value could be negative. We could also use tardiness which is non-negative lateness, the maximum of the difference between the lateness and zero.

Ad-hoc changes and the usage of non-regular capacity are direct consequences of unmet milestones. AWL promises delivery dates towards customers and aims to achieve these. As a result, ad-hoc changes and non-regular capacity are needed to achieve these promised due-dates.

A planning strategy divided in a strategic, tactical and operational level helps to overcome this problem. This research investigates the current planning stragety at AWL and indicates how to improve or redesign this method by incorporating a strategic, tactical and operational planning level in such a way that AWL is able to create a more reliable plan per project.

1.3 Previous research at AWL

This sections discusses the main findings of previous research at AWL and provides background information for this research. Two theses are completed at AWL several years ago. Providing insight in their research is important because we want to know why their recommendations are not or partially implemented. Next to that, overlap in research should be prevented. Section 1.3.1 discusses the research of Meijerink (2003). Section 1.3.2 discusses the research of Evers (2013).

1.3.1 Research of Chantal Meijerink

Meijerink (2003) conducted research in the field of the importance of a capacity oriented planning for AWL. The research objective was to give insight in the importance of capacity planning for AWL. She made several recommendations for AWL which are partially implemented. The recommendations that are not followed up are:

Uncertainty or variability should be taken into account in the planning methodology.
This recommendation is partially implemented at AWL. Tactical planners plan longer lead-times to deal with this uncertainty or variability. However, there is no buffer visible in the tactical plan. In addition, the existing planning tools are not supportive enough to take this uncertainty and variability into account automatically.

Planning should be done, taking capacity restrictions into account, rather than just looking at lead times and further research is needed into how to properly achieve this at AWL.
This recommendation is not implemented by AWL. A capacity check is performed only afterwards. This implies that AWL plans against infinite capacity. In addition, the effects of changes in a project plan is not incorporated.

1.3.2 Research of Jeroen Evers

The research objective of Evers (2013) was: 'Give advice for the applicability of recently developed methods and algorithms for planning and show the potential benefit for AWL'. Evers (2013) mentioned explicitly that the mathematical model of Chantal Meijerink is not followed up. He therefore focussed on implementation of tactical algorithms. In order to do so, he used algorithms to calculate the potential benefit for AWL regarding multi-project planning at a tactical level.

The two most important recommendations of his research were:

AWL should employ a multi-project planning algorithm for tactical planning.
The recommendations provided in the research have not yet been implemented. Implementing this algorithm will probably yield AWL significantly better results. However, the supporting planning tools that AWL has available are not advanced enough to implement this algorithm.

The communication lines and responsibilities of the tactical planning function and project management should be altered.
This recommendation is partially taken into account. At the moment, there are two 'tactical planners' and two 'operational planners'. However, once the assembly phase starts, tactical planners are not responsible for a project plan anymore. Project coordinators take over this responsibility.

1.4 Research design

This section formulates the research goal and the corresponding research question and sub-research questions. Section 1.4.1 formulates the research goal. Section 1.4.2 composes the research questions for this research. Finally, Section 1.4.3 provides the scope of this research.

1.4.1 Research goal

We formulate the research goal as follows:

'Provide a renewed planning strategy and illustrate the impact and the requirements for the redesign'

This research goal results in the following research question:

'*How should the planning strategy of AWL be redesigned such that the number of unmet milestones is minimized?'*

The aim of this research is to answer this question and to provide insight in the following aspects:

- Analyse the current way of planning and the encountered problems with this way of working.
- Provide insight in the gaps between the situation at AWL and the available literature.
- Show how these gaps can be covered for AWL and describe the consequences of redesigning the current planning method.
- Describe how the new planning strategy can be deployed at AWL.

1.4.2 Research questions

We formulate research questions to answer the central research question. These questions form the structure of this research. We divide the different research questions on chapter basis.

Research question 1: What is currently known in literature on capacity planning in an ETO-environment?

1.1) Which methods for capacity planning in an ETO-environment have been proposed in literature?

We provide an overview of existing literature regarding capacity planning in an ETO-environment in Chapter 2.

Research questions 2: How is the current assembly and planning process organized?

2.1) What are the main activities of the assembly process?
2.2) What does the current planning process of the assembly department look like?
2.3) Who are responsible for the different planning functions?
2.4) What is the current performance of the planning process?
2.5) What are factors that cause discrepancy between the initial planning made and the realization of this planning?

We describe the current situation in Chapter 3 and determine the current performance of the planning process. Factors that cause discrepancy between the initial plan made and the realization of this plan are important to investigate before addressing an alternative way of working. We obtain information for Chapter 3 via the Intranet of AWL and via interviews with employees.

Research question 3: What is an optimal planning strategy for AWL?

3.1) How should the redesign of the current planning strategy look?
3.2) How should the communication structure look like to enable this new planning strategy?

In Chapter 4, we develop a renewed planning strategy for AWL that incorporates the knowledge obtained via literature. Here we address the gaps found between the current situation and literature. In addition, we explain what multi-project planning should look like for AWL.

Research question 4: How should the improved planning strategy be deployed at AWL?

4.1) What are the steps for deploying the improved planning strategy at the entire facility?
4.2) Are the available tools suitable for the renewed planning strategy?
4.3) What are the consequences of the redesign for AWL?

In Chapter 5 we provide a roadmap that describes how AWL can enrol the improved planning strategy.

Finally, we present our conclusions and recommendations in Chapter 6.

1.4.3 Scope

It is important to scope the problem, since both the problem and the scope of this research are broad. This research focuses on the analysis of the current planning process and on the theoretical design of an improvement of the planning process. Furthermore, we analyse how this alternative planning strategy can be deployed at AWL. Implementation of the new planning strategy is not part of the research.

Chapter 2: Literature review

This chapter reviews relevant literature in the area of production planning. The literature review is built up in different sections. Section 2.1 determines the position of the Customer Order Decoupling Point (CODP) of AWL. Section 2.2 describes the hierarchical framework and the purposes of the different planning levels. Section 2.3 provides a state-of-the art review of tactical planning methods for ETO organizations. We mainly focus on tactical planning in this chapter since we see in Chapter 3, that the core problem concerns the tactical planning level.

2.1 Determination of the CODP for AWL

The CODP is the point where demand specifications get frozen and is defined as 'the point in the value chain for a product, where the product is linked to a specific customer order' (Olhager, 2010). This means that activities before the CODP are forecast driven while activities after the CODP are driven by customer demand.

Olhager (2010) distinguishes between four different manufacturing situations.
1. Make-to-stock (MTS)
2. Assemble-to-order (ATO)
3. Make-to-order (MTO)
4. Engineering-to-order (ETO)

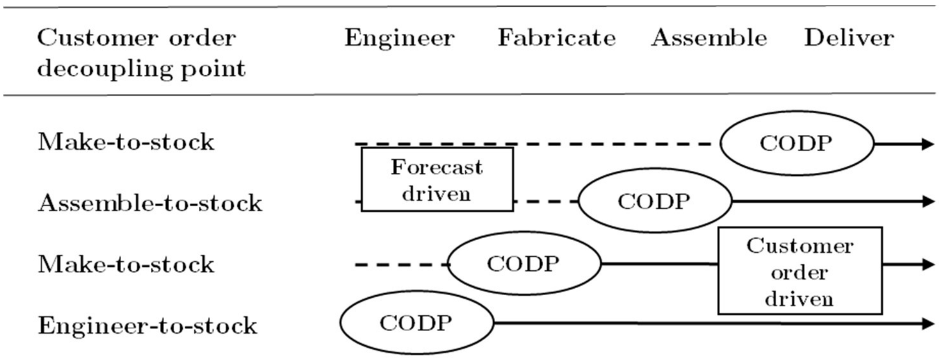

Figure 2.1: Determination of the CODP (Olhager, 2010)

In Figure 2.1 shows that the CODP for ETO environments is already at the engineering department. This implies that all activities are customer-order driven. The customer may frequently require changes in the design, which results in a high dependency of customer requirements. In addition, ETO organizations have to cope with a high degree of variability because every project is new to the organization. This is the case at AWL since every project is a new project, if an order is not a repeat order. Every order is unique and activities are entirely driven by customer demand.

AWL is working on standardization by developing subassemblies. Working with subassemblies results in a standardized assembling process and makes it possible to execute assembly activities simultaneously. However, the project stays unique because the combination of subassemblies (robots, tools and jigs) is different for each project. Standardized subassemblies will require engineering work in the future, because sub-assemblies need adjustments according to customer requirements. Hence, a project may consist of standardized components but remains unique. Based on this, we conclude that AWL is an ETO organization.

2.2 Hierarchical planning framework

This section presents a hierarchical framework for planning and control in manufacturing environments. The framework is partly based on De Boer (1998) and altered by Hans et al. (2005). The framework supports project-driven organizations that face uncertainty. It is meant to break the production planning down in smaller more manageable parts and can be used to identify planning and control issues and scope their interventions. Furthermore, the framework serves as a tool to differentiate different planning functions at an organization.

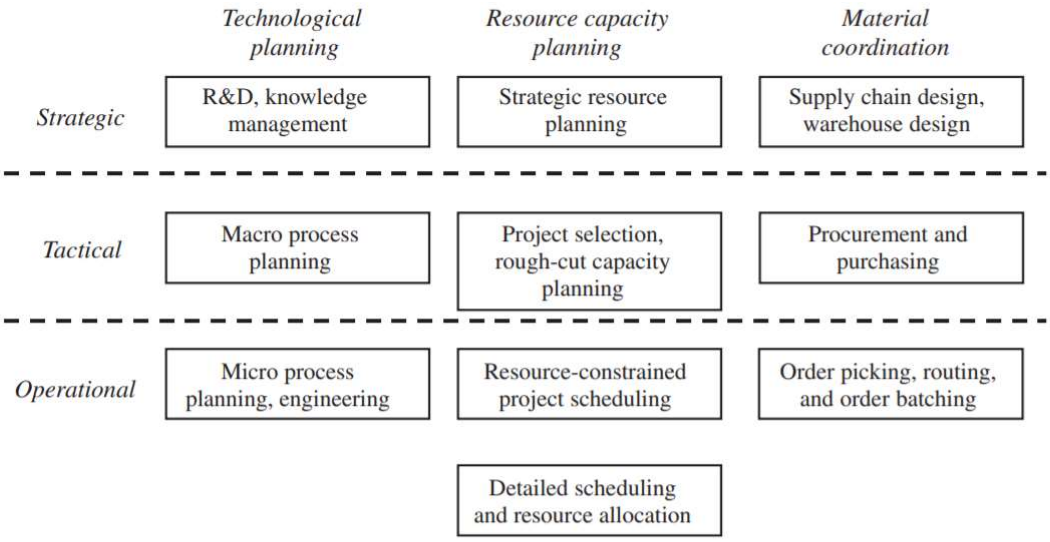

Figure 2.2: Hierarchical planning framework (Hans et al., 2005)

The framework consists of three hierarchical levels: 1. Strategic level, 2. Tactical level and 3. Operational level. The framework has three different pillars: 1. Technological planning, 2. Resource capacity planning and 3. Material coordination.

2.2.1 Strategic planning level

Strategic planning addresses the structural decision making. A long term plan is made at the strategic planning level that identifies how to achieve goals for an organization. Most of the times, the planning horizon ranges from one to five years (Olhager, 1999). According to Zijm (2000) activities at this level are long range forecasting, sales planning, demand management and aggregate planning. Aggregate planning concerns workforce planning, subcontracting, marketing and product planning.

Olhager (1999) states that long-term capacity management considers capacities that take a long time to change. Input to long-term capacity management is a sales plan, based on a demand forecast. The sales plan should be translated into a capacity plan later on. Most organizations use a Manufacturing Resource Planning (MRP or MRP II) system to support Manufacturing Planning and Control (MPC). According to Jin and Thomson (2003), MRP systems do not satisfactorily meet the needs of ETO organizations. There are several reasons for this. First of all, MRP is Bill of Material (BOM) oriented. However, in ETO environments BOMs are not completely defined at the order acceptance phase (Jin and Thomson, 2003). In addition, these systems do not use finite capacity planning. MRP and MRP II use fixed lead-times instead of work-load dependent lead times and the system is material oriented instead of process or capacity oriented.

Decisions regarding capacity, facilities and production progress are considered as structural decisions and therefore part of long-term company goals. It is of strategic importance to decide whether capacity should be adjusted according to changes in demand or whether capacity should come first (Olhager, 1999).

Capacity planning at the strategic level is often done using a Linear Programming (LP) or Mixed Integer Programming (MIP) model.

The available information at the strategic planning level is not detailed enough to make an actual planning. However, this level provides the structure for the next to hierarchical levels, tactical and operational planning.

2.2.2 Tactical planning level

The tactical planning level is a middle-level activity which connects the strategic planning and the operational level. At this level, a project is viewed as a set of project activities with both precedence relations and relations. The basic problem is the allocation of resources such as capacity, work force availability, storage and resource distribution over a medium range planning horizon (Bushuev, 2014). Activities at the tactical level are project selection, also called order acceptance and rough-cut capacity planning (RCCP) (Hans et al., 2005).

Many organizations try to sell as much as possible without considering the status of the production system. It is hard to estimate the impact on the actual available capacity. This implies that order acceptance and production planning is often functionally dispersed. Hence, order acceptance is not based on the actual workload. This results in an overloaded system and promising unrealistic due dates to customers. In other words, when order acceptance is not based on the actual workload, there is no resource flexibility and no flexibility in time (Hans et al., 2005).

At the tactical level, there is a significant amount of uncertainty because it is not known which orders are placed yet. In addition, details of production orders are unknown which makes it hard to estimate the required resources for a set of orders. On the other hand (reliable) due dates have to be promised to customers. This makes the tactical level a complex planning level which is often underexposed. The tactical level contains flexibility in terms of time and capacity. This means that either due dates of customers can be soft, i.e. postponed or capacity can be extended.

Several questions arise during the order acceptance phase. It should be determined whether delivery dates can be met, how much capacity is required for an order and how much non-regular capacity is allowed. The problem to deal with these questions is called the Rough Cut Capacity Planning (RCCP) problem. RCCP methods use flexibility in time and capacity to support planning in making a trade-off between expected delivery performance and the expected costs of exploiting flexibility by using non-regular capacity (De Boer, 1998). Reliable and effective RCCP has a positive impact on the variability on the operational level and functions as input for order acceptance. RCCP gives insight in how to divide (non-regular) capacity over multiple projects and indicates how to react to disturbances by building a robust project plan. A robust project plan means avoiding system nervousness (De Boer, 1998).

De Boer (1998) distinguishes between two different kinds of RCCP, either resource or time driven. The available capacity is fixed in resource driven RCCP. However, due dates are soft. The objective function tries to minimize the maximum lateness. In a time driven RCCP, due dates are hard, also called deadlines. Capacity is extendable in this variant. The objective function tries to minimize the use of non-regular capacity. In reality, a combination of the two might occur, called a hybrid approach.

2.2.3 Operational planning level

As one goes down in the hierarchical structure, the horizon of decisions decreases and the level of detail increases. Scheduling of detailed activities is done at the operational planning level and concerns execution of short-term activities. Typically, the planning horizon at this level ranges between a day and a week. The goal is to schedule all work and assign the right resources to the right activities within the given time frame. Objectives that can be used to optimize this level are for example: maximize utilization, minimize tardiness (i.e. non-negative lateness), minimize set-up times and minimize work in process for example. The schedule made assumes a given workload and a given amount of available resources. This means that detailed information is required for this planning level. The problem to be solved at this level is called the Resource-Constrained Project Scheduling Problem (RCPSP). It differs significantly from RCCP and that is why different planning levels are required. Two reasons why RCPSP and RCCP differ significantly are:

- RCPSP assumes fixed capacity since it is often impossible to increase capacity in the short term. However, RCCP is both flexible in time and capacity.
- RCPSP needs detailed information, however detailed information is unknown at the tactical stage. RCCP functions with less detailed information and is suitable for the tactical level.

According to Hans et al. (2005) the operational planning level can be further divided into an online and offline level. Offline approaches make a priori decisions and have a finite decision horizon. Online approaches react directly to every change.

2.3 State-of-the-art review of tactical planning methods in ETO-environments

This section provides a state-of-the-art literature review regarding tactical planning in ETO-environments. We classify the different articles found in Table 2.1. Furthermore, we elaborate on the objective and most important aspects of these articles. Since we are interested in the recent developments, we focus on the published literature in the last fifteen years.

Tactical planning is of high importance for ETO organizations, because these organizations are constrained by various scarce resources. Therefore, decisions regarding resource allocation are crucial in the ETO context and are related to setting important milestones for each project and bid preparations. (Gademann and Schutten, 2005; Hans et al., 2005).

Many algorithms are addressed to MTO organizations, for example Gademann and Schutten (2005), Hans (2001), Wullink (2005), Ballestin et al. (2007), Corti et al.(2006) and Ebben et al. (2005). Fewer algorithms are specifically addressed to ETO organizations, for example Kis (2004), Masmoudi et al. (2011), Alfieri et al. (2011), Cherkaoui et al. (2015) and Calvalho et al. (2015). It is important to distinguish between ETO and MTO because these organizations have different characteristics which may require a different planning method.

According to Hans (2001), MTO organizations are typically characterized by non-repetitive production of small batches of special products. These products are usually combinations of standard components. On the other hand, ETO organizations build complex customized structures and are tailored to the customer requirements.

2.3.1 Classification of planning methods

We classify the different models found in literature. A distinction is made between deterministic and models that incorporate uncertainty. Models that incorporate uncertainty can be further divided into fuzzy models and stochastic models.

Deterministic models

Most proposed models in literature regarding tactical planning assume deterministic input data and do not take uncertainty explicitly into account. This is highly questionable assumption according to Wullink (2005), since there is a high uncertainty level, especially in ETO environments. At the tactical level examples of uncertainties are release date, workload estimation, capacity availability or procurement delays (Wullink, 2005; Masmoudi et al., 2011; Carvalho et al., 2015). Many deterministic models do not take these kinds of uncertainties into account, but model robustness against uncertainty by adding slack to the model (Cherkaoui et al., 2017).

Models that incorporate uncertainty

In practice, input data is often uncertain, especially in ETO environments. Wullink (2005) states that deterministic models are not suitable for production environments with uncertainty. Uncertain models can be further divided in stochastic or fuzzy models.

Fuzziness is a type of imprecision that has no well-defined boundaries for its description (Cheraghalikhani et al., 2019). Fuzzy project scheduling assumes that activity durations rely on human estimations and is more appropriate when few and imprecise information is available (Wullink, 2005). For example, when workload is vaguely described and requires on average 100 to 140 hours, but in extreme cases can require 80 or 180 hours.

Stochastic models are usually based on the concept of randomness and are limited to tackle uncertainties with probability distributions (Cheraghalikhani et al., 2019). This means that it is unknown in advance which activity is going to be executed and for how long. Simulation is often used for stochastic models due to the computational complexity (Wullink, 2005).

2.3.2 Overview of articles found

The articles found are classified in Table 2.1 based on the classification scheme. Table 2.1 provides the oversight of the different articles and their main characteristics.

Per reference we give the model type, the objective function, the kind of non-regular capacity used and the type of precedence relations. We distinguish between standard finish-to-start precedence relations, which forces predecessor activities to complete entirely before starting the successor and feeding precedence relations, which allow a certain amount of overlap among activities.

Reference	Model type	Objective function	Non-regular capacity	Precedence relations
Wullink (2005)	Stochastic	Minimization of costs over all scenarios	Overtime, hiring and subcontracting	Finish-to-start
Kis (2004)	Deterministic	Minimization resource relations violation	Not defined	Finish-to-start and feeding
Masmoudi et al. (2011)	Fuzzy	Maximization of robustness or minimization of costs	Overtime, hiring and subcontracting	Not defined
Alfieri et al. (2011)	Deterministic	Minimization of the make span	Not defined	Feeding
Naber and Kolisch (2014)	Deterministic	Minimization of the make span	Not defined	Finish-to-start and feeding
Carvalho et al. (2015)	Deterministic	Cost minimization	Overtime, hiring and subcontracting	Feeding
Cherkaoui et al. (2015)	Deterministic	Cost minimization of non-regular capacity	Not defined	Finish-to-start
Baydoun and Hait (2016)	Deterministic	Minimization of the make span or project costs	Not defined	Feeding with rework
Naber (2017)	Deterministic	Minimization of the make span	Not defined	Not defined
Cherkaoui et al. (2017)	Deterministic	Cost minimization of non-regular capacity	Overtime, hiring and subcontracting	Not defined

Table 2.1: Overview of found literature

2.3.3 Main characteristics of articles found

In this section we review the main characteristics of the articles found.

Wullink (2005) questions the deterministic assumption and proposes a MILP model that deals with uncertainty. Several scenarios are composed to model uncertainty. Wullink (2005) extends the exact branch-and-price model which is a deterministic case proposed by Hans (2001) to the scenario-based problem. A scenario is a case in which each uncertain job occurs in a specific mode. A mode is a limited number of work contents per uncertain job that may occur. The modes are assumed to be independent. In other words, the different stochastic variables are independent. The research of Wullink (2005) shows that scenario based RCCP yields plans with significantly lower expected costs. However, the plan is computationally very intensive due to the large MILP model.

Kis (2004) proposes a model in with variable intensities and feeding precedence relations. Variable intensities describe the executing of activities when the amount of work performed in a time bucket is not fixed, but depends on resources. Feeding precedence relations are needed when project activities might overlap. Standard finish-to-start precedence relations does not allow overlapping. However, it happens often in practice. Kis (2004) introduces feeding precedence relations to literature. The model Kis (2004) proposes is formulated as a MILP and solved using the branch-and-cut algorithm. Branch-and-cut is a branch-and-bound based algorithm that makes the possible solution space smaller by introducing cutting planes. The author concludes that a model with feeding precedence relations seems easier to solve in terms of computational time.

Alfieri et al. (2011) extend the work of Kis (2004) by modelling four types of feeding precedence relations.

a) %Completed-to-Start: the successor activity can only start if a predetermined percentage of predecessor activity is already completed. (Figure 2.3a)
b) %Completed to finish: the successor activity can only be completed when a predetermined percentage of the predecessor activity has been completed. (Figure 2.3c)
c) Start-to%Completed: the execution of the successor activity can only proceed if a predetermined percentage of the predecessor activity is already completed. (Figure 2.3b)
d) Finish-to-%Completed: the execution of the successor activity can only proceed a predetermined percentage if the predecessor activity has been completed. (Figure 2.3d)

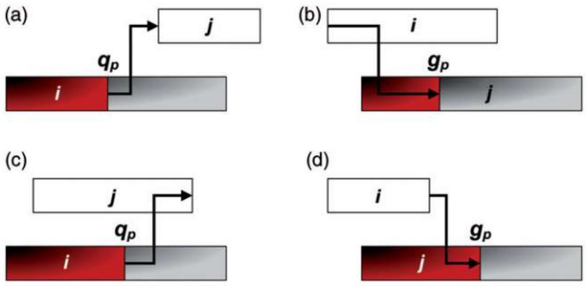

Figure 2.3: Feeding precedence relations (Alfieri et al., 2011)

The authors conclude that the model is impractical for a large number of instances. It is only appropriate for a maximum of 60 activities.

Masmoudi et al. (2011) present a model based on a fuzzy approach since assuming deterministic input data is not a realistic assumption. A fuzzy approach is useful when few and imprecise information is available. The Fuzzy Rough-Cut Capacity Problem (FRCCP) problem is solved via a simulated annealing heuristic.

Naber and Kolisch (2014) address the Flexible Resource-Constrained Project Scheduling Problem (FRCPS). It happens often in practice that resource profiles are not constant but vary over time. In FRCPS, the resource profile can be specified per period. The authors propose four different models to model the FRCPS. The best model is the model containing both variable intensity activities and feeding precedence relations. However, the solution requires more computation time because of the large number of variables and relations.

Carvalho et al. (2015) provide an action research in the ETO environment. The MILP formulation includes feeding precedence relations and variable intensity of activities. The model provides a pragmatic view of what can be obtained from a mathematical model in an ETO context.

Cherkaoui et al. (2015) propose a time driven RCCP with different planning levels. These different planning levels are created by varying the length of time periods. The model considers shorter period lengths at the beginning of the planning and activities become more aggregated at a further horizon. All proposed models in literature divide the planning horizon into equal lengths, assuming that the accuracy of data is the same for all periods. This is an unrealistic assumption. Cherkaoui et al. (2015) therefore suggest to divide the planning horizon into periods of variable length. The periods become larger as we advance in time. The model performs better in terms of computational time compared to a standard model since it aggregates periods.

Naber (2017) presents a model that contains both continuous and discrete time periods. The model of Naber and Kolisch (2014) contains discrete time periods. Discrete time periods use a predetermined fixed duration. The result may be suboptimal. Therefore, Naber (2017) extends the model proposed by Naber and Kolisch (2014) by proposing continuous time periods as well. The major advantage of using continuous time slots is the reduction of binary variables and relations. However, the model becomes more complex and is harder to solve. Therefore, the model requires more computational time.

Baydoun and Hait (2016) consider rework in addition to overlapping. The models of Kis (2004) and Alfieri et al. (2011) do not take reworks into account. The proposed model is an extension of the RCCP model proposed by Hait and Baydoun (2012). The model adds a third type of events: intermediate milestones. These milestones show the development of aggregate activities. The computation time of the model increases when the percentage of possible overlapping couples increases because the model becomes more complex.

Cherkaoui et al. (2017) consider a proactive time driven RCCP with variable period lengths. A proactive approach builds robustness in the model to be resistant to future disruptions. A reactive approach is able to re-optimize when a disruption occurs. The paper uses a capacity buffering strategy. Calculations showed that the proposed approach proves to be effective regardless the uncertainty in project activities.

2.3.4 Concluding remarks

We draw some conclusions after examining the published articles regarding tactical planning in the ETO environment in the last fifteen year. An important contribution to literature is the mathematical modelling of feeding precedence relations, introduced by Kis (2004). His work is extended by Alfieri et al. (2011). Furthermore, Baydoun and Hait (2016) include rework in the feeding precedence relations by introducing intermediate milestones. Carvalho et al. (2015) present an action research by implementing the exact model at an ETO organization. We see that the gap between literature and practice is still large when it comes to tactical planning. It is hard or even impossible to implement the proposed models in practice because the problem instance becomes too large and computing a solution takes too much computational time (Carvalho et al., 2015; Alfieri et al., 2011). Further research is required regarding the implementation of tactical planning in practice. We see that many tools are proposed but only a few are implemented in real life organizations. Tactical planning decision tools support planners during the order acceptance or rejection phase and for due date settings. In addition, tactical planning tools help to identify the potential gap between capacity and demand and can demonstrate how to balance demand (Calvalho et al., 2015). Implementation of tactical planning decision tools is therefore valuable for organizations.

2.4 Conclusion

This chapter provided a theoretical analysis of the research area. Section 2.1 analysed the position of the CODP for AWL and concluded that AWL is an ETO organization. After that we introduced the hierarchical planning framework and explained the different planning levels and their importance. Section 2.3 gave a state-of-the-art review about tactical planning in ETO environments. We concluded that the gap between literature and practice is still large. Literature proposes multiple algorithms, but only a few are implemented in practice.

Chapter 3: Analysis of the current situation

This chapter describes the current situation at AWL. Section 3.1 describes the main activities of the assembly process. It is important to understand the main activities of the primary processes before describing the planning process in-depth. Section 3.2 explains the current planning process. Section 3.3 describes the different stakeholders and their performance measures. Section 3.4 discusses the current performance measures used to evaluate the planning process. Section 3.5 describes the encountered problems.

3.1 Main activities of the primary process

This section describes the main activities of the primary process. The main activities form the backbone for a more detailed description of the current planning process. Figure 3.1 describes the sequence in which different departments execute their activities. The subsections of this paragraph explain the main activities of these departments sequentially.

3.1.1 Sales department

The sales department is responsible for obtaining customer orders. The process of accepting an order proceeds as follows: the customer sends a request for quotation (RfQ) to AWL and the sales department starts their process, which consists of six different steps.

The first step is 'Lead qualification'. In this step a salesman registers a RfQ and determines whether a request can be accepted or not. Order acceptance is done via an 'opportunity log': an Excel file in which several questions have to be answered regarding acceptance or rejection of an opportunity. A possible incoming order is called an opportunity within AWL. Order acceptance at AWL is not based on the actual available capacity in the assembly phase. In other words, the sales department of AWL accepts as many opportunities as they possibly can without considering the effect on the other departments.

In the second step 'Determine demand', a team determines the exact customer demand, by consulting with the customer about their requirements.

The engineering department is already involved during the sales process. Concept engineers devise a possible solution during the third step, 'Determine solution'. From this stage on, the planning department and cost engineers are also involved. Cost engineers make a rough cost calculation of the devised solution. The planning department makes an estimation of the throughput time for this opportunity, called an opportunity plan. The opportunity plan is based on customer requirements and customer milestones. The opportunity plan gives an indication of the throughput time for this order and is made for a single project without considering the available capacity and the effect on other projects.

The fourth step is called 'Create proposal'. Concept engineers make a detailed solution after acceptance of the concept by the customer in this step.

Step five and six are the 'Negotiation' and 'Hand over' phases respectively. In these phases the negotiation process of an order takes place and the project is handed over to the project management department.

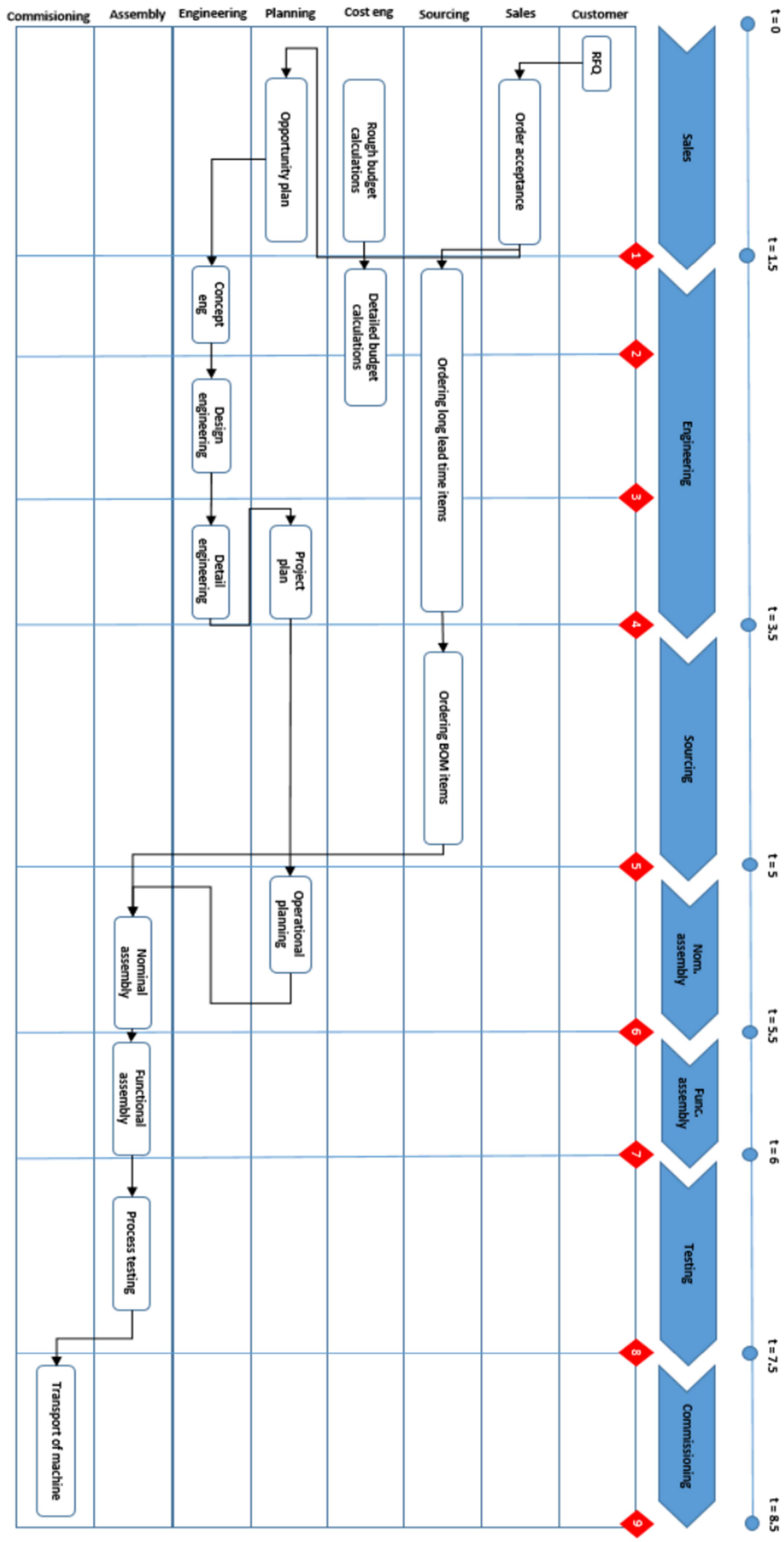

Figure 3.1: Primary process of AWL

3.1.2 Engineering

The engineering department designs and develops new machines and innovative solutions for customer orders. A project leader is assigned to a new project and held responsible for the project. The engineering process can be divided into three steps:

- Concept engineering: development of an engineering concept
- Design engineering: alter and improve the design of the concept
- Detail engineering: detail the design according to customer requirements

The first step is the development of an engineering concept. The engineering department develops a conceptual idea that meets the customer requirements. A concept freeze takes place after completion of this conceptual design. The design engineering phase starts after acceptance of the customer order. The design of the machine cells and jigs is completed when requested changes of customers are processed and altered in the design. The last step is the detail engineering phase. The remaining design details are engineered in this step. The design can be released for production after completion of these steps. Figure 3.2 shows a jig of a machine cell that is designed during the engineering phase.

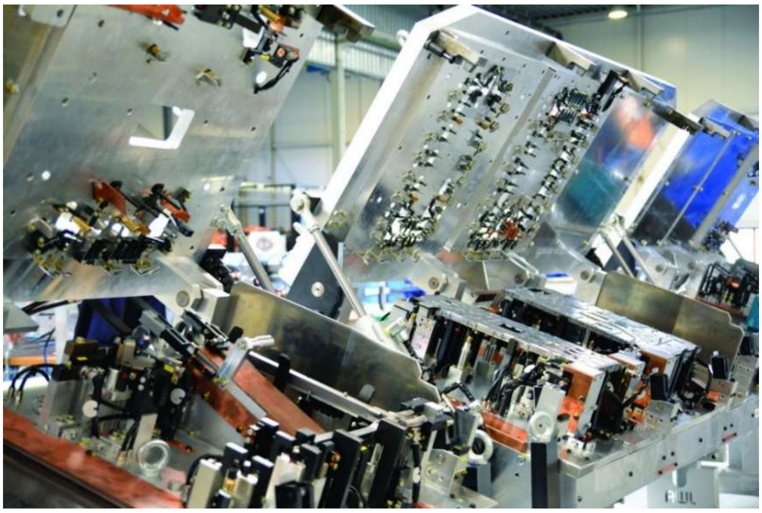

Figure 3.2: Jig of a machine cell (Brains: Intranet, AWL)

3.1.3 Sourcing

The bill of materials (BOM) is released after the ‘release for production’ decision. A make-or-buy decision is made for all the items of the BOM. Subsequently, a tendering process starts if the company decides to buy the items instead of making the required items. The items of the BOM are collected in the warehouse before the start of the assembly phase. Long lead time items are already ordered during the engineering phase. The sourcing process is performed by the logistic department and takes six weeks for each project.

3.1.4 Assembly

The assembly process consists of several phases. We explain these phases one by one.

Nominal assembly

The machine cell is built from scratch. A machine cell is the product that AWL delivers towards the customer. The result of this assembly phase is a completely built machine cell. However, the machine is not functioning because the software is not installed yet. An example of a machine cell is visualized in Figure 3.3 and shows the most standard machine cell AWL assembles, called Basic Arc.

Nominal commissioning
Software has to be installed on the machine in order to make the machine functional. During the nominal commissioning phase, software installation is prepared. Tests have to be executed, for example I/O tests and installations of software programs have to be prepared.

Functional assembly
The software is installed on the machine hardware in this assembly phase. The machine cell is operational after completion of this phase. Software programmers with specific skills are required. For example, some programmers are able to program a specific robot in a specific programming language. The final result of this phase is functioning hardware and software.

Figure 3.3: Basic Arc machine cell (Brains: intranet, AWL)

Process optimization
The machine is able to produce parts, however several aspects have to be tested and adjusted. This is done during the process optimization phase. The customer specific requirements, for example cycle time, are tested and adjusted in this phase.

3.1.5 Commissioning

The final step is the acceptance of the machine cell by the customer. Project management decides whether the machine can be commissioned. A final acceptance test is conducted before transportation to the customer.

3.1.6 Service

The service department provides aftercare, incident management and administrative tasks. These services can both be fulfilled at AWL or at the customer side and are seen as supportive processes.

3.2 Current planning process

This section describes the current planning process. The planning department is responsible for the project planning and capacity monitoring. The planning structure of AWL is divided in three hierarchical levels, the strategic, tactical and operational level. We elaborate on these three levels consecutively.

3.2.1 Strategic planning level

At the strategic level a long-term plan, the strategy plan, is made to realize the mission and vision of AWL. The strategy has a horizon of five years. Input for this strategy plan are the mission and vision of the company. Output are strategic performance indicators and a yearly order intake.

In addition, a business plan is made at this planning level. AWL announces a target order intake for the global organization. This target value is further divided in the different sectors AWL operates in: seating, body, special projects, CRN and service. Thereafter, the order intake is further divided into the different facilities. Next to that, a global estimation of the required number of employees per facility is made at the strategic level. This is called: the human resource plan.

Figure 3.4 shows the order intake per segment in 2018. The order intake varies significantly over time and results in an unbalanced workload.

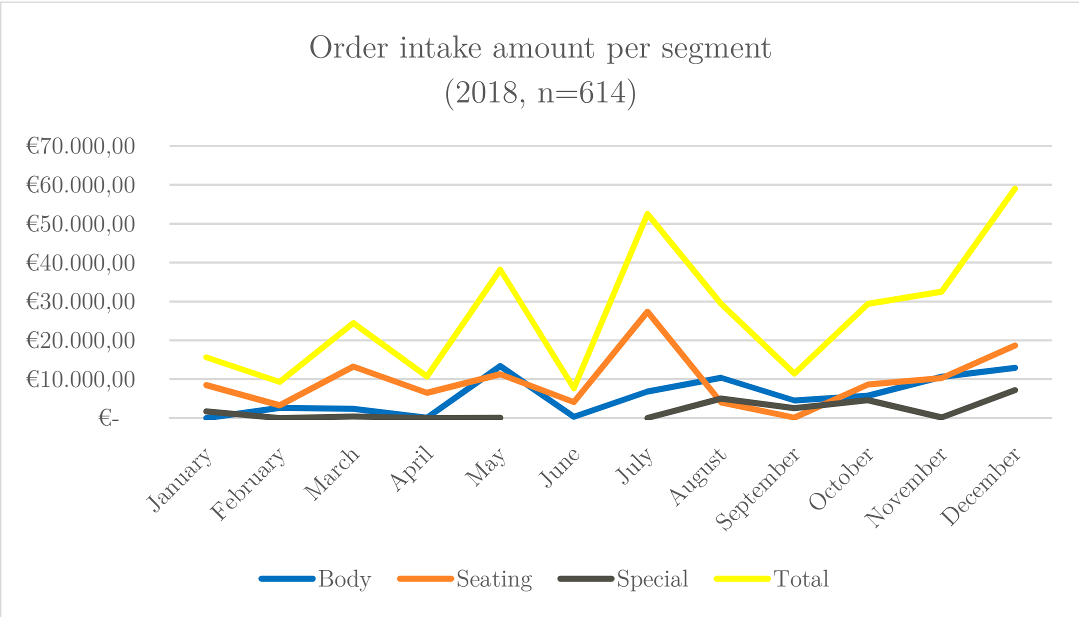

Figure 3.4: Order intake amount per segment in 2018 (Navision, AWL)

3.2.2 Tactical planning level

Tactical planners fulfil the planning tasks at the tactical planning level. Tactical planners are held responsible for four main activities:

1) Determination of the project throughput time
2) Determination of the project delivery date
3) Release of project plan
4) Making mutation in the project plan

Determination of project throughput time

One of the major tasks of the tactical planning department is to determine the throughput time of projects. AWL needs to assure that customer milestones can be completed on time. Due dates of milestones are discussed in the negotiation process. The tactical planner takes these customer milestones into account and makes a throughput time estimation based on customer milestones. This plan is called the opportunity plan, as explained in Section 3.1.1. The opportunity plan is made in 'isolation' meaning that the impact on other projects is not considered and infinite capacity is assumed. This way of working is called single-project planning with infinite capacity. The throughput time estimation is currently based upon personal planning experience or consultation with the department project management.

Determination of the project delivery date

The tactical planners perform a capacity check after the throughput time estimation. This check is executed based on the 'capacity plan'. The term 'capacity plan' is misleading. The 'capacity plan' is not an actual plan but a representation of the total number of available assembly hours. Furthermore, the project plan is not based on the available capacity. In other words, the throughput times are not based on the available capacity. The tactical planner checks whether the requested milestones of customers can be met with the available capacity. The utilization is measured in the 'capacity plan' and is calculated by dividing the planned hours by the total capacity. Currently, the utilization of the operational process is aimed at 95% or higher. This goal is extremely high for an operational process and results in no flexibility against uncertainty or variability in the process.

Release project plan

More project details become gradually available after completion of the project tender. A completely new plan is made based on more detailed information. This means that a project plan is made twice. The second project plan is more accurate since more details are available. The project leader and project coordinators are responsible for the project from here on.
Currently, no buffer is visual in the project plan. This means that every start- and end time of an activity planned in advance is exactly equal to the duration of an activity. Tactical planners plan longer lead times than the actual duration of the activity. Employees are aware of the available slack in the planned throughput time. This results in a phenomenon observed in literature called the 'planning loop'. Fixed lead times leads to the tendency to postpone activities because employees know that several activities can be executed at a later point in time than indicated in the planning. However, the likeliness of not meeting the target increases due to postponing and employees start complaining about too short lead times which results in, again, increased lead-times. To conclude, AWL does not have an accurate idea of the actual workload of an activity. This results in planner longer lead times than the actual duration of an activity.

Appendix I visualizes an example of a project plan. Appendix I shows that project activities are not planned. The project plan only indicates the lead time for a department. The activities that a department fulfils are currently not defined in a project plan.

Mutate project plan

Customers may require changes in the design during the entire engineering and assembly process. This happens quite often in practice. The tactical planner has to adjust the project plan based upon these changing customer requirements. We see that the tactical plan at AWL is currently based on throughput times and a capacity check afterwards. In addition, we see that the effects on other projects is not considered while making a new project plan. The responsibilities of the tactical planners is transferred to project leaders once the tactical plan is completed. Operational planners make many manual adjustments which are focused on a single project. The effects of these changes on other projects are not considered in the current planning method. Table 3.1 presents the current input and output data for a project plan.

Input single-project plan	**Output single-project plan**
Customer deadline of the project	Throughput time per project
Number of budgeted hours per project	Start and end time per department
Customer milestones: • Project start • Pre-acceptance • Final acceptance	Milestones for engineering and assembly department: • Kick off assembly • Nominal ready • Functional acceptance • Internal acceptance • Pre-acceptance • Final acceptance

Table 3.1: Used input and output data for tactical plan

3.2.3 Operational planning level

The project planning indicates the start- and due date per phase of the assembly process. This can be seen in Appendix I. Project activities are not scheduled in a project plan. Assigning employees to operational activities, called project tasks from hereon, is one of the responsibilities of the operational planners. The operational planners work with a weekly plan cycle. All requests for changes in the initial project plan for the next two weeks have to be sent to the operational planners before Wednesday. These requests will be processed before Friday of that week. A proposal that comes in later will be processed the next week. However, the operational planner processes the proposal if the proposal cannot wait this long. These proposals are called ‘out of control’. Operational planners and team leaders meet once a week to discuss open planning issues and to find possible solutions: increasing capacity of the department, outsourcing activities or reconsidering the current plan made.

A project coordinator makes an operational schedule and send requests of specific employees for an activity to an operational planner. This implies that many schedules are made and every project team has their own schedule. A capacity request can be done by a project coordinator in the planning tool by proposing “Dummies”. Dummies are fictional employees. Operational planners accept or decline these requests and allocate resources to project tasks in the planning tool. The operational planner checks the impact on other projects manually and checks whether that specific employees with corresponding competences are still available. It is one of the main tasks of the operational planners to check and assign these capacity requests.

Another task of the operational planners is hiring additional staff (e.g. non-regular capacity). If the requests of project coordinators is higher than the available capacity, additional staff have to be hired. Operational planners are held responsible for this task. This means that at the operational level, there is both flexibility in terms of capacity and in time. According to literature, this should only be the case at the tactical level (De Boer, 1998). According to De Boer (1998), Hans et al. (2005) and Wullink (2005), only flexibility in time is possible at the operational level.

Stakeholders at the operational level are both the project leader and the project coordinator as well as the operational planners. The project leader is responsible for multiple projects. The project coordinator decides on the estimated capacity and sends a request towards the operational planner. The operational planner is responsible for assigning the requested capacity.

In addition, operational planners propose possible solutions for changing the project plan. The operational planner searches for available staff in the changed project plan.

Table 3.2 shows the used input and output data for making an operational schedule.

Input operational schedule	Output operational schedule
Release date per project	Assigned employees per resource group per activity
Activities per project	Start- and end date per activity
Required resource group per activity	Required non-regular capacity
Budgeted hours per activity	Total planned hours per project

Table 3.2: Used input and output data operational schedule

3.3 Stakeholders and performance measures

This section shows the involved stakeholders for the planning process according to the hierarchical planning framework. The stakeholders are identified per planning level and briefly introduced. In addition, the most important performance measures for these stakeholders are mentioned.

3.3.1 Strategic planning level

The management of AWL and the sales department are stakeholders at this planning level. The management consists of the board of directors for the global organization: CEO, COO, CFO and the Global Sales director. In addition, the managing director is also a stakeholder at this level. The sales department is responsible for estimating the order intake per year. They must estimate this number and verify this with the management of AWL.

Performance measures for the strategic level in 2018 are shown in Table 3.3

Realized order intake per year: 250-300M euro per year
Operational utilization > 95%
EBITDA > 11%
Solvability > 30%

Table 3.3: Performance measures strategic level (Strategic plan, AWL)

3.3.2 Tactical planning level

The sales department, tactical planners and the operations manager are stakeholders at the tactical planning level. Order acceptance or rejection is currently determined by the sales department. Resource capacity loading is a responsibility of the tactical planners. Below we provide performance measures for the sales department and the operations manager respectively.

Sales department	Operational manager
Realized order intake per month	Percentage of milestones completed on time
Intake amount per FTE	Work in progress per month
Work in progress per month	Utilization per resource group

Table 3.4: Performance measures tactical level

3.3.3 Operational planning level

Stakeholders at the operational planning level are operational planners, project coordinators and operators. Requesting operators for an activity is done by project coordinators. Operational planners are responsible for scheduling the operators. Performance measures for the operational planners, project coordinators, team leaders and operators are mentioned in Table 3.5.

Operational planners	**Project coordinates**	**Operators**
Utilization per resource group	Milestones completed on time	Overtime
Number of dummy hours	Number of changes of personnel in project team	Material availability
Out of control actions per week	-	Distribution of workload
Number of changes in operational plan	-	Number of personnel changes in project team
Usage of non-regular capacity per resource group	-	-

Table 3.5: Performance measures operational level

3.4 Performance of current planning process

This section shows the performance of the current planning process. The KPIs used are: 1. Percentage of milestones completed on time. 2. Deviation of budgeted hours from booked hours per resource group. 3. Percentage of hired capacity 4. Percentage and costs of hiring additional staff and 5. Utilization of different resource groups.

Percentage of milestones completed in time

In this research we focus on the following milestones 1. Concept Freeze (engineering department), 2. Design freeze (engineering department), 3. Released for production (engineering department), 4.Kick-off assembly (assembly department), 5. Nominal assembly (assembly department), 6. Functional acceptance (assembly department), 7. Internal acceptance (assembly department), 8. Pre-acceptance (assembly department), 9. Final Acceptance (assembly department) in this sequence. Table 3.6 displays the percentage of milestones completed in time in 2018.

Milestones	**Percentage completed on time in 2018 n= 136**
Concept freeze	59%
Design freeze	43%
Released for production	63%
Kick-off assembly	51%
Nominal assembly	52%
Functional acceptance	50%
Internal acceptance	44%
Pre-acceptance	68%
Final acceptance	72%

Table 3.6: Percentage of milestones completed on time (Navision, AWL)

We see that the overall percentage of milestones completed in time is low. However, the percentage of completed milestones rises when further phases of the project are reached. This rising percentage can be explained by incorporating slack in the project plan. Building slack in the project plan results in some spare time to finish remaining tasks. We conclude that this slack gives enough time to finish 72% of the projects before the customer due date. Figure 3.5 focusses on the last three milestones and shows that there is a lot of overlap and delay between different activities in 2018.

The delay and overlap are caused by the planning against infinite capacity, multiple operational changes and scarce resource availability in the functional assembly phase. Delay and overlap result in unmet milestones in 2018.

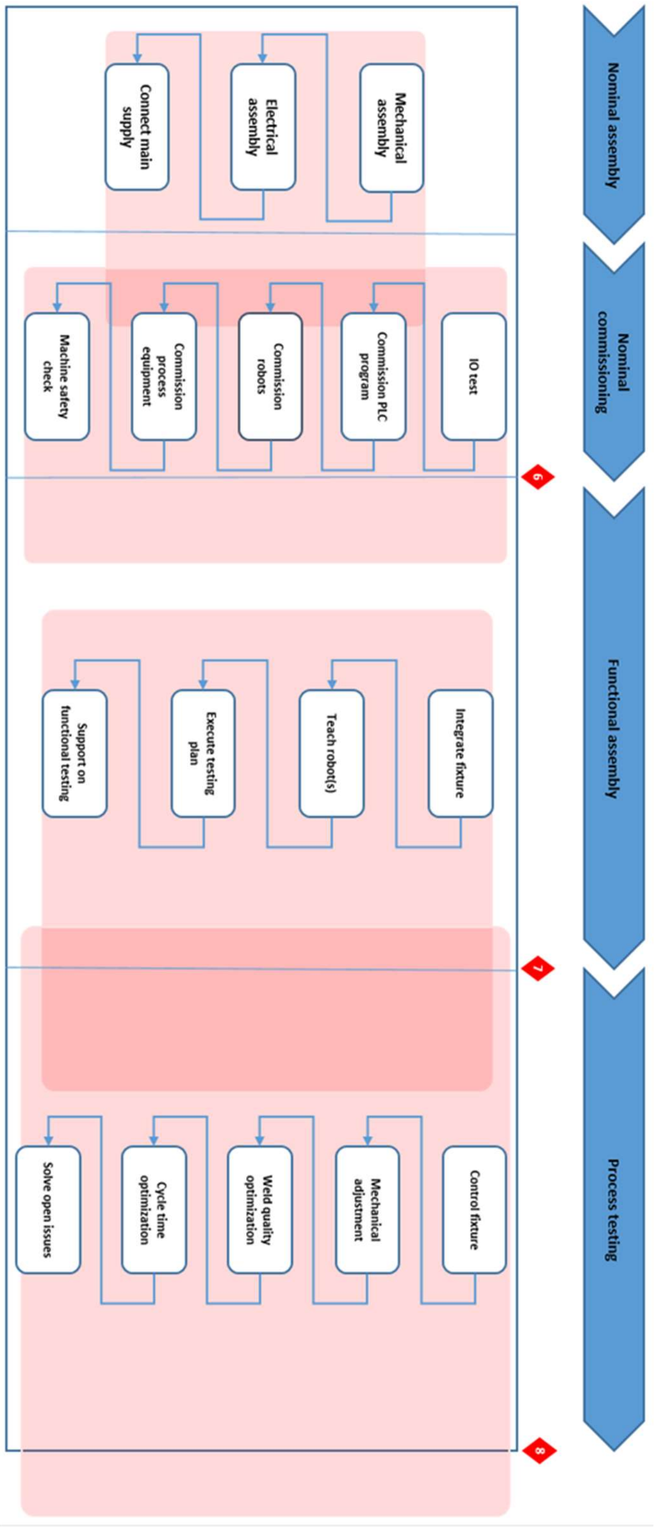

Figure 3.5: Delay at assembly department (n=132)

Deviation between budgeted hours and booked hours per resource group in 2018

This KPI measures the deviation (in percentage) between the budgeted and booked hours per resource group in 2018. The budgeted hours are an estimation of the required assembly hours and are used for the price calculation of a project. The booked hours are the realization of the assembly phase. The deviation gives an indication of the accuracy of the budget estimation. The planning is based on the budgeted hours estimation. Consequently, the accuracy of the budgeted hours influences the accuracy of the planning. The different project activities are 1. Mechanical assembly, 2. Electrical wiring, 3. PLC programming, 4. Robot programming.

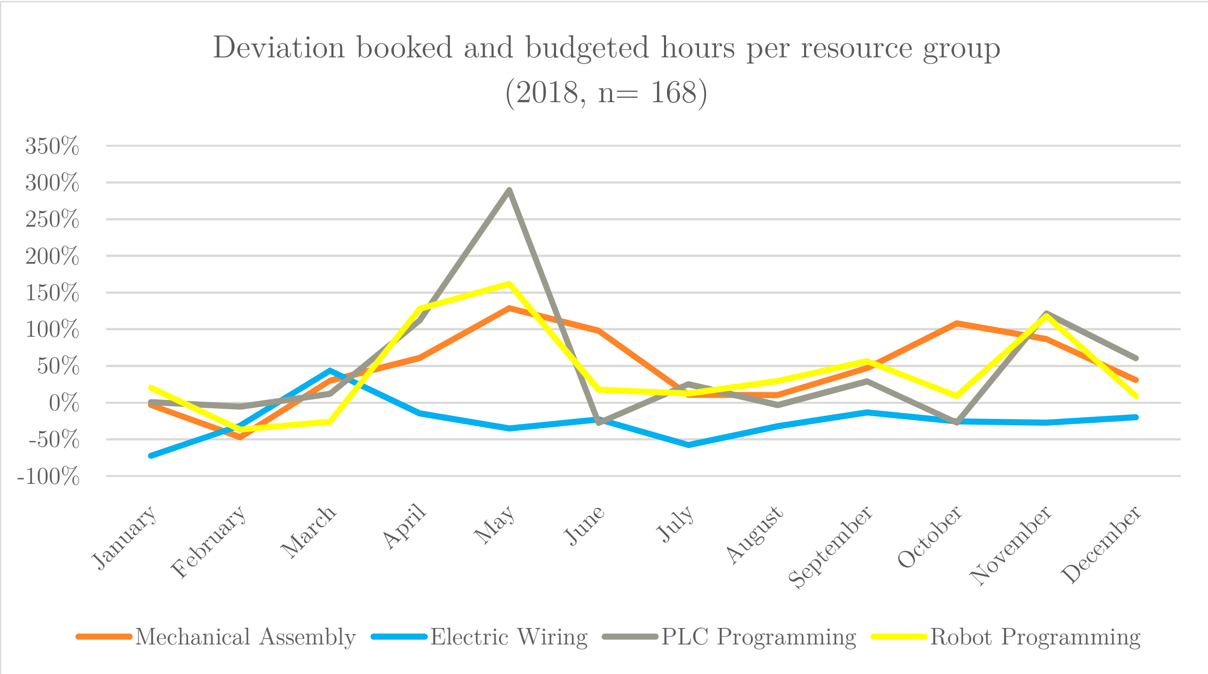

Figure 3.6: Deviation budgeted and booked hours per resource group (Navision, AWL)

Figure 3.6 indicates the large deviation between the budgeted and booked hours. More hours are booked than budgeted if the percentage in Figure 3.6 is positive. If the deviation percentage is negative, the number of booked hours are lower than the budgeted hours. We see that difference can be extreme, especially for PLC programming; almost 400%.

Percentage of hired capacity

This KPI indicates the percentage of hired capacity in the second half of 2018. It is possible to hire employees for every resource group. The percentage of hired capacity is calculated by dividing the number of hired FTEs by the number of FTEs employed by AWL. Figure 3.7 shows that almost all resource groups hire extra capacity, especially PLC programmers need extra capacity. Hiring extra capacity is a consequence of accepting as many orders as possible and making a project plan in isolation.

A remarkable fact is the percentage of hired PLC programmers in August, which is above 90% while less hours are booked than budgeted for this resource group. However, the utilization of PLC programmers in August is almost 100%, which means that the hired capacity was needed. Hence, the estimation of budgeted hours for PLC programmers in August was incorrect.

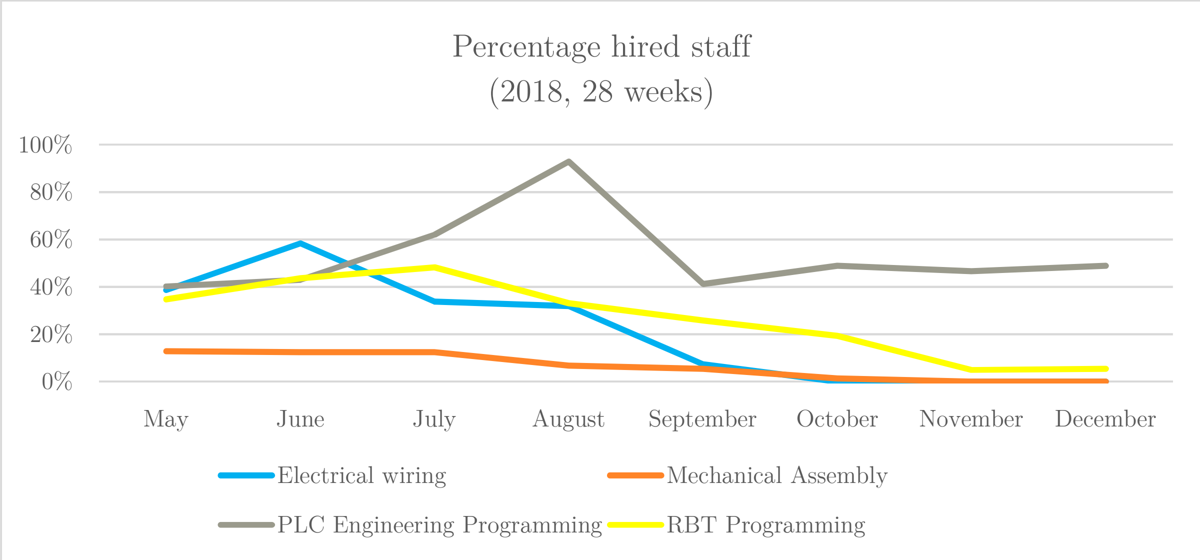

Figure 3.7: Percentage of hired personnel 2018 (Navision, AWL)

Table 3.7 shows the costs of hiring extra employees for these seven months in 2018. We compared the regular salary of an employee per resource group with the salary of a hired employee to make this calculation. In these seven months, AWL had additional expenditures for hired personnel of about €281.063,00.

Resource group	Percentage hired	Costs hiring
Electrical wiring	21%	€69.360
Mechanical assembly	6%	€23.448
PLC Programming	53%	€81.457
Robot Programming	27%	€101.798
Average/total	27%	€281.063

Table 3.7: Costs of hiring personnel 2018 (Navision, AWL)

Percentage worked in overtime

This KPI shows the percentage and corresponding costs of working in overtime in 2018 for four different resource groups. To calculate the costs of overtime, we counted the additional costs of working in overtime. The large difference between the costs of overtime is due to the different hour salary and the different number of FTEs per resource group.

Resource group	Percentage overtime	Costs overtime
Electrical wiring	19%	€63.023
Mechanical assembly	12%	€111.679
PLC Programming	10%	€77.304
Robot Programming	13%	€108.084
Average/total	14%	€360.090

Table 3.8: Costs of working in overtime 2018 (Navision, AWL)

We have to mention that the costs of hiring additional employees and working in overtime is not only due to poor planning activities, but also due to the difficulty of obtaining adequate staff.

Utilization of the assembly

High utilization of resources is important for AWL. The board of AWL aims for an operational utilization of at least 95%. This number is very high for an operational process and results in low robustness against variability. However, we want to provide insight in the utilization because it is important for the current state of the planning process. Figure 3.8 shows the utilization for the four different resource groups. We conclude that the utilization of robot programmers is extremely high. The percentage of hired robot programmers in these seven months is 50% at most, while the utilization of robot programmers in the months May till October is always above 100%, sometimes it is even 180%. High utilization leads to decreased flexibility against process variability, for example variability in the processing times. A highly loaded system will not be able to cope with processing time variability as queues will form in the system. These queues lead to longer lead times per project, hence more work in progress.

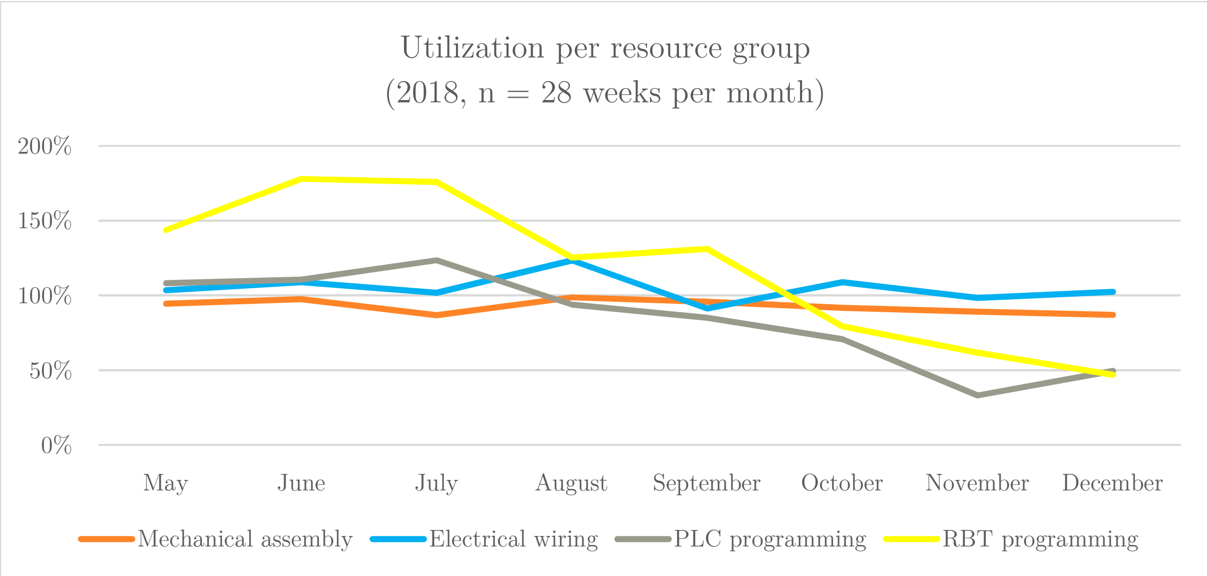

Figure 3.8: Utilization of the assembly department (Navision, AWL)

In addition, the utilization of the PLC programmers in the months October till December is 50% on average, while the percentage of hired employees is also equal to 50%. It is remarkable to hire 50% of the employees while the utilization is also equal to 50%. The estimation of required personnel for this month was probably incorrect.

3.5 Encountered problems

This section mentions the encountered problems that cause variation in the current planning process. The problems are divided in a strategic, tactical an operational level respectively.

3.5.1 Problems at the strategic level

Yearly target order intake is unrealistic

The estimated order intake of AWL is structurally too high. This results in a fictional pressure on existing resources. In addition, employees at AWL know that this estimation is too high. The trustworthiness is lower because of this reason.

Order intake does not result in a stable workload

Figure 3.4 shows the fluctuation in order intake per segment in 2018. The large peaks in demand result in an unstable workload for the assembly department. The large peaks are caused by accepting as many order as possible, rather than basing order acceptance upon available capacity.

AWL accepts as many orders as possible

AWL operates according to a chase strategy. AWL retains most customers if the customer satisfaction is high enough. Recurrence of customers is of strategic importance for AWL. This may result in acceptance of an order when the assembly department is already scheduled at full capacity. This causes problems and delays for other projects.

Reward structure of sales results in infinite order acceptance

The employees at the sales department receive a bonus above their standard salary per sold project. This reward structure encourages selling as much as possible. However, it makes the gap between the available capacity and the sold project even larger. It might be the case that selling an extra project results in usage of non-regular capacity or even penalties of customers since projects are delivered too late. In such a case, AWL has to pay twice. First of all, AWL pays a bonus for the sales employee. Second of all, AWL pays extra for non-regular capacity.

3.5.2 Problems at the tactical level

Project plan is made in isolation

A project plan is currently made in isolation. This means that the effect on other projects is not incorporated in a project plan and infinite capacity is assumed. This way of working results in ad-hoc changes in the operational level.

Project plan is based on throughput times, rather than available capacity

The project plan is based upon throughput times. Throughput times are estimated by the tactical planner based upon experience. A capacity check is only executed afterwards. If required, changes in the project plan can be made. The usage of non-regular capacity is not seen as a problem, since the progress of the project is more important than exceeding capacity.

Using fixed lead-times result in the planning loop

Buffers or slack are not visualized in the project plan. The planned lead time is always longer than the required time to finish the workload. In addition, the exact required workload per activity is unknown. Operators are aware of this and postpone activities. This phenomenon is called the ‘planning loop’.

AWL assumes it has a capacity plan but this term is misleading
AWL performs a capacity check after the throughput time calculation. The capacity check is performed via a ‘capacity plan’. However, this is a representation of the total available hours per resource group.

The tactical plan is not based on the available capacity. Therefore, this term is misleading. This causes confusion within the company.

Project activities are not defined in a project plan
A project plan only indicates the lead time per department. The activities that a department performs are currently not defined. This implies that the project plan is not an actual ‘plan’, but only a representation of the lead time per department.

Precedence relations are not mapped
Project activities have precedence relations. Some activities must be executed sequentially while other activities can be executed in parallel. Precedence relations are currently not mapped. Without mapping the precedence relations, manual adjustments are required to alter all successive project activities.

Milestones are not respected by employees
Many employees are involved in making a project plan. Not every employee sees milestones as hard deadlines. The importance of these milestones is therefore low for employees. AWL keeps track of these milestones but the lack of urgency misses when it comes to milestones.

3.5.3 Problems at the operational level

Insufficient support of the operational planning tool
The operational planning tool, the AWL planner, distributes the available capacity evenly over the weeks. Capacity is defined as the number of available FTEs. In practice, activities require less capacity at the beginning and at the end of an activity. However, the AWL planner is not able to take this into account. This results in an unreliable capacity distribution. Operational planners are aware of the lack and alter the project plan manually.

Project coordinators are also responsible for operational planning
Project coordinators request employees for a project and make their own project plan. The operational planner is only responsible for allocating the requested resources to the specific tasks. This implies that many employees are involved for making a detailed project schedule. In addition, every project coordinator and team leader have their own way of making an operational plan. Different ways of making an operational schedule cause confusion within the company.

Many ad-hoc changes are required in the operational plan
The project plan made at the tactical planning level is made in isolation. Hence, the effect on other projects is not incorporated. In practice, multi-project with finite capacity is required. This results in many ad-hoc changes at the operational planning level.

3.6 Conclusion

This section concludes Chapter 3. We described the main activities of the primary process and the current planning process at AWL. The stakeholders are analysed and the most important performance measures and encountered problems are mentioned. We conclude the following:

- Although AWL is a multi-project organization with finite capacity, a project plan is made in isolation based on infinite capacity. A capacity check is only executed afterwards.
- The term used within AWL for 'capacity plan' is misleading since it is only a summation of the available hours of employees.
- The project plan requires many manual adjustments. We indicated that the planning tools are not able to support the planning process at AWL in the right way.
- There is no buffer visual in the project plan. A direct consequence is that employees have the tendency to postpone activities. The exact duration and slack of an activity is unknown. This results in increasing lead-times, also called 'the planning loop'.
- The KPI utilization is important within AWL. The target is set at 95% or higher. In other words, AWL tries to maximize the utilization. In reality, this results in less robustness against variability. Maximizing the utilization results in maximizing the waiting times.

The remainder of this research focusses on the importance of multi-project planning with finite capacity for AWL. We emphasize the following aspects:

- We show the gaps between the current situation at AWL and the available literature.
- We show how these gaps can be covered and describe the possible benefits of multi-project planning for AWL.

The research indicates the importance of a new planning strategy and gives advice on how this can be deployed at AWL.

Chapter 4: Gap analysis and implementation of the planning framework

This chapter applies the hierarchical planning framework on the observed situation at AWL. First, we map the current situation at AWL in the planning framework in Section 4.1. In addition, we identify absent or lacking planning functions and explain the current level of integration between different planning functions. Mapping the current situation of AWL in the framework enables us to redesign the content of the framework. Section 4.2 redesigns the content of the planning framework for AWL. Section 4.3 focuses on the tactical planning level and explains what multi-project planning should look like at AWL. We discuss aspects like, the planning horizon, the required input and output data, the project activities, required stakeholders and their responsibilities. In addition, we explain the how the different planning functions and planning levels should interact in practice.

4.1 Mapping the current situation of AWL in the planning framework

The planning framework can be used to identify missing planning functions and planning problems. The missing planning functions and planning problems are identified with the aid of experts and theory. Experts at AWL are planners, the manager operations and the managing director. After identification of the absent planning functions, we focus on the lack of coherence between planning functions by explaining the current interaction and integration between different hierarchical levels of control at AWL.

4.1.1 Identification of absent planning functions

In Chapter 3, we analysed the current situation. Applying the hierarchical planning framework on the observed situation, we are able to identify lacking planning functions. We discuss our findings for the different hierarchical levels of control sequentially.

Strategic level

No long term demand forecasting and aggregate capacity management method

Comparing the activities that AWL performs at the strategic level (see Section 3.2.1) with a theoretical perspective (see Section 2.2.1) and with opinions of experts of AWL, we conclude that there is no-long term demand forecast and aggregate capacity management method present at AWL. AWL limits itself to a yearly order intake and expected revenue for that year. There is no sales or demand plan based on historical data with a longer horizon than two months. As a result, AWL has no forecast for the workload for the coming period.

Tactical level

No method available for resource capacity loading and order acceptance

Based on our analysis of the current tactical planning process, we were able to conclude that each project plan is made in isolation. Planning multiple projects simultaneously results in multi-project planning with infinite capacity. The fixed lead times are used in the project plan with a certain buffer since the actual workload of an activity is currently unknown. This way of working results in the ‘planning loop’, since postponement is tempting and therefore lead times tend to increase.

In addition, we observed that the yearly order intake appeared to be unrealistic, since it is adjusted downwards several times a year. The unrealistic yearly order intake encourages the sales department to accept as many orders as possible without considering the actual workload of an order. This results in an imbalance between order acceptance and loading a set of orders to specific resource groups. These imbalances lead to an overloaded production system, where unrealistic due dates are promised to customers. The direct consequence for AWL is little resource flexibility and no flexibility in time.

Operational level

Missing project scheduling tool

Section 3.2.3 explained that project coordinators and team leaders have autonomy of a project once the tactical planners release the project plan for production. Project coordinators make a detailed operational schedule per project without interaction with other project coordinators. Every project coordinator has his own way of making a detailed schedule. There is no tool available to assist the project coordinators or that creates a standardized detailed schedule. This way of working results in several detailed schedules made separately from each other. Project coordinators are not aware of the different operational schedules executed at the same point in time. As a direct result, project coordinators try to reserve specific employees in advance, which may lead to sub-optimal resource allocation. The autonomy lies with the project coordinators because of the variability of the project pathway. It is hard to predict the operational steps of the entire project pathway in advance.

In conclusion, there is no method or tool available to supports making a detailed schedule. So, comparing the current situation with theory and the opinion of experts results in the conclusion that there is no project scheduling tool available.

4.1.2 Overview of the current hierarchical planning framework

Projecting the absent planning functions on the hierarchical framework of Hans et al. (2005), leads to the current state of the hierarchical framework tailored for AWL.

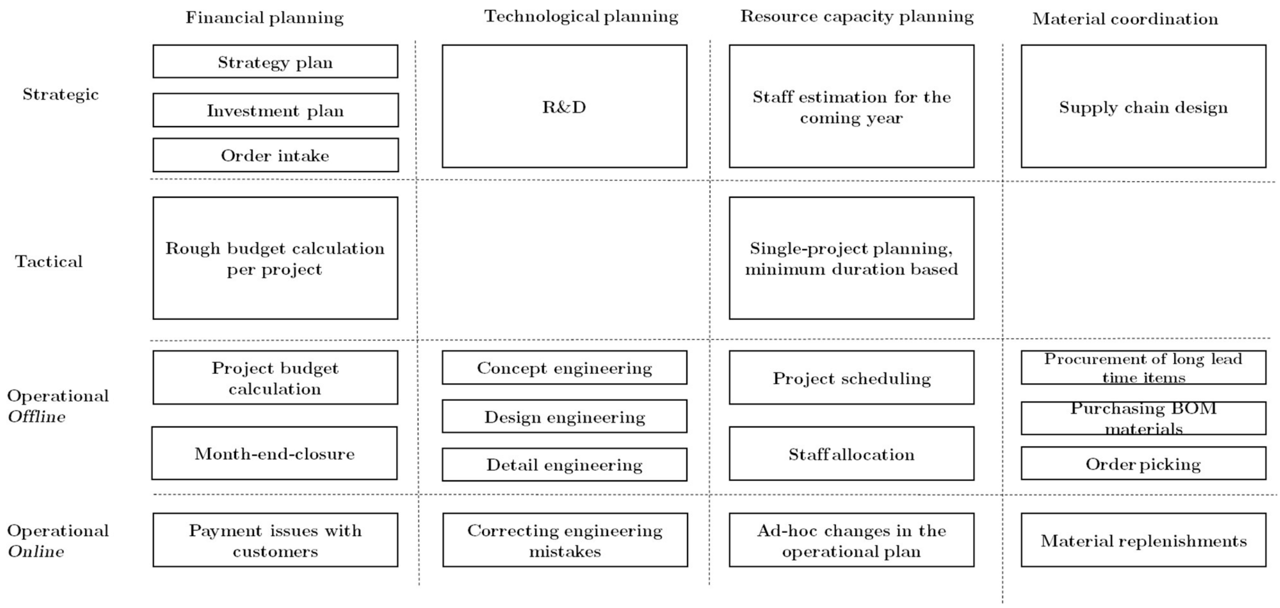

Figure 4.1: Content of the hierarchical framework based upon the observed situation at AWL

The placement of planning functions in Figure 4.1 is based on the content of Table III.1 in Appendix III. The content of this table is based on our own observations, which are validated by experts at AWL.

For AWL, the planning horizon for activities at the strategic level is two years. For the tactical level, the horizon is at most the length of one project cycle, which is nine months approximately.

The data for making a project plan and budget calculation are based on estimations, since details are not available yet. We therefore placed these activities at the tactical level of control. Activities that are currently executed when detailed project data becomes available are positioned at the operational *offline* level.

For example, the demand and supply plan have a horizon of two months, while the duration of one project is nine months on average. This implies that demand and supply are matched on daily basis, which belongs to the operational level of control. Furthermore, engineering activities are currently performed when the exact project content and customer requirements are known. We therefore placed engineering at the operational level of control as well.

Based on this observation we confirm our conclusion made earlier: the tactical level is overlooked and poorly addressed by AWL. The strategic level of control is mainly concerned with financial issues while managers tend to focus on the operations which is called 'the real time hype'.

4.1.3 Current integration and interaction between the planning functions

We explain the current interaction and integration between planning functions by explaining the meetings per level of control. This is important because, next to absence of planning functions, the lack of coherence between different planning functions is indicated as one of the problems that occur in organizations (Hans et al., 2005).

Strategic level

Based on the opinion of experts we state that there are no structural meetings held at the strategic level that interact with stakeholders of other control levels. However, the board of directors presents the performance of AWL every quarter of the year to employees. So, every quartile AWL reviews the performance and adjusts its targets based upon this review. This observation implies interaction between the strategic level and the operational level. However, interaction with the tactical level is currently undefined.

Tactical level

Figure 4.1 shows the activities per level of control. Planning a project and roughly calculating the budget is done individually for each project. There is currently no meeting that discusses issues regarding these two activities. Originally, AWL intended to set up a S&OP meeting and a demand and supply plan at the tactical level. However, due to the frequency of the meeting and level of detail of issues discussed during these meetings we defined these meetings as operational meetings.

Operational level

AWL introduced a 'weekly plan cycle' several months ago. Operational issues that arise during the assembly process are discussed during this weekly meeting. The meeting functions as horizontal integration between different planning functions at the operational level, ranging from engineering issues to material related problems.

The S&OP meeting is intended to integrate the vertical levels of control, to provide objectives from higher hierarchical levels to lower levels of control and provide feedback from the lower hierarchical level of the performance of the operational level. The meeting discusses newly acquired projects, possible problems with supply and demand and issues that were addressed during the weekly plan cycle meeting.

We compose Figure 4.2 based upon our observation. Figure 4.2 visualizes the current interaction between the different plans made for each level of control. In addition, the figure indicates the financial, technological and resource capacity aspects that are discussed per meeting by the stakeholders. We conclude that there is currently no interaction with the tactical level.

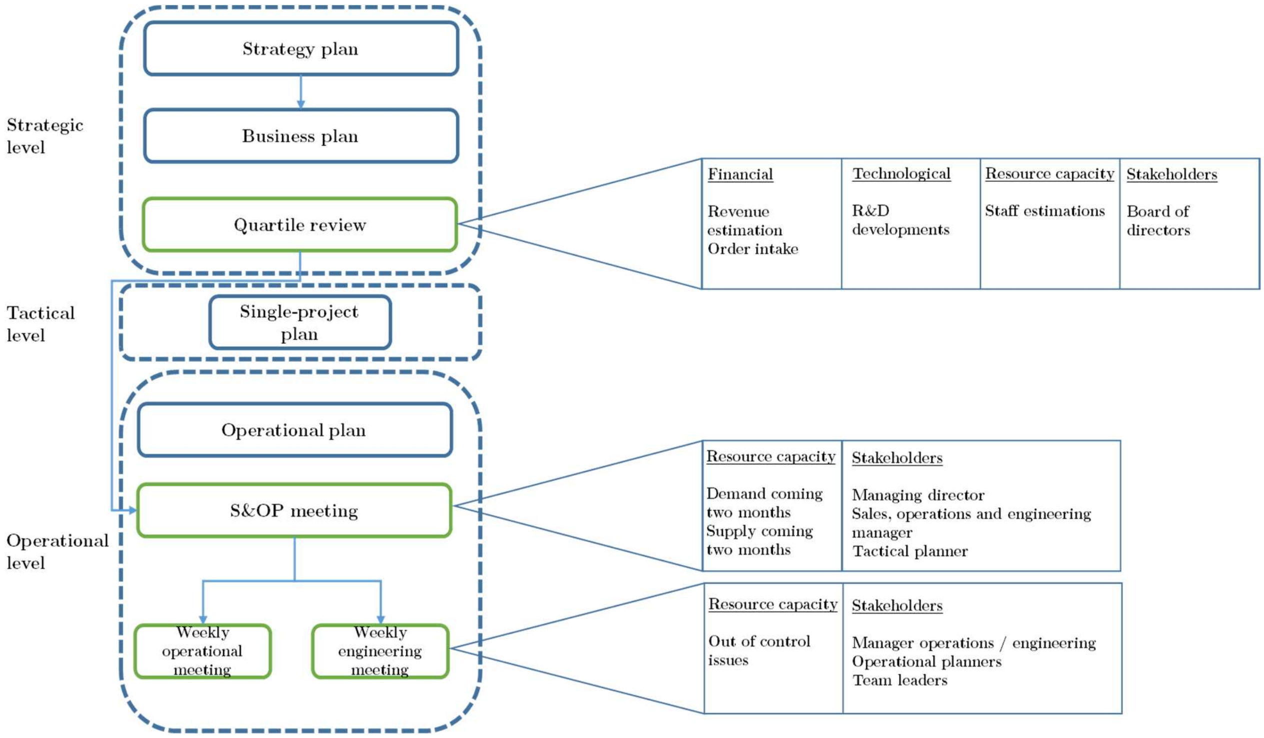

Figure 4.2: Current integration structure between different levels of control at AWL

4.2 Redesign of the hierarchical planning framework for AWL

This section proposes a redesign of the hierarchical planning framework for AWL. The redesign is made because we identified lacking planning functions. The redesign is based on our observation of the current situation, discussions with experts and our theoretical analysis. We explain how we made a distinction between the different hierarchical levels and managerial areas within the framework tailored for AWL.

4.2.1 Redesign and application of the framework

Figure 4.3 shows the redesign of the hierarchical planning framework for AWL. For each hierarchical level, we observe difference between aspects, like: scope of decisions, level of data aggregation, decision maker(s) and stakeholder(s) and arising uncertainties. Based on this we are able to distinguish between five different hierarchical control levels and four different managerial areas. In Sections 4.2.2 and 4.2.3 we explain the rationale behind the different control levels and the content of the framework.

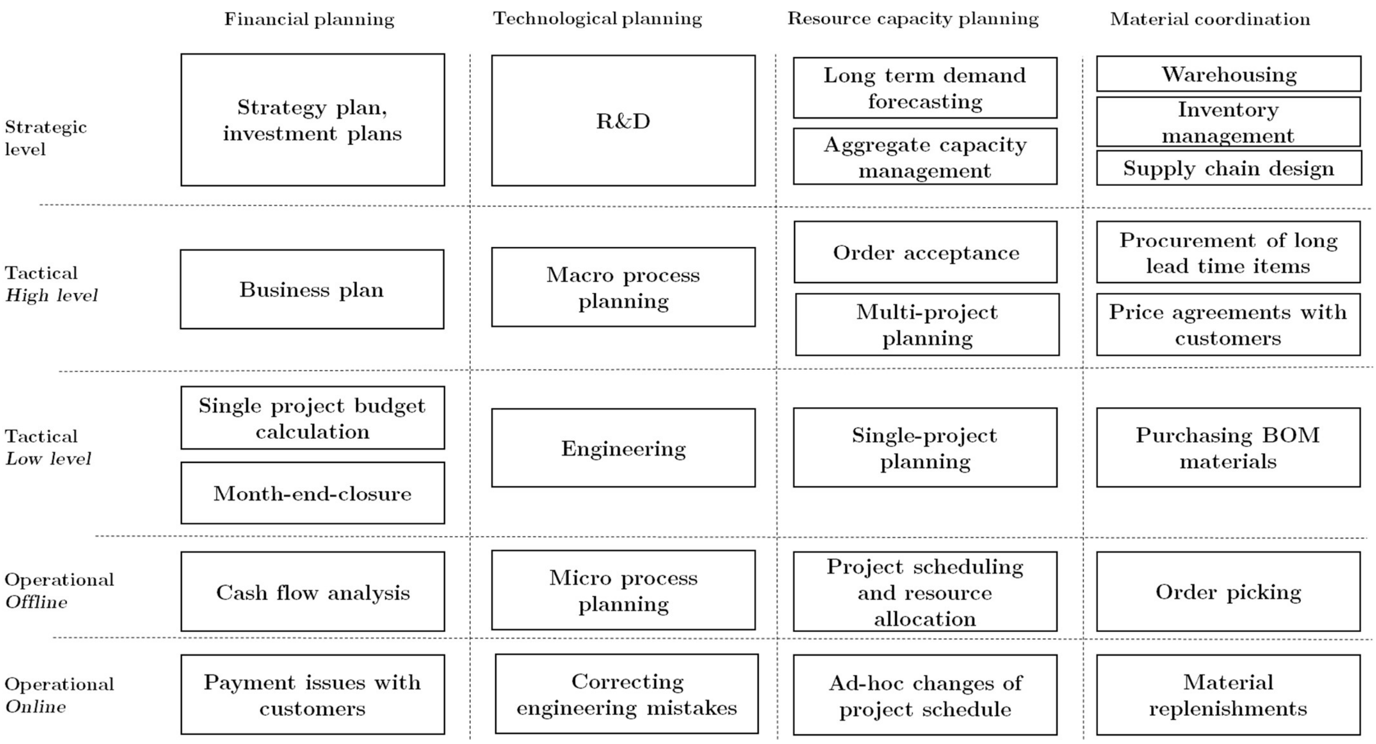

Figure 4.3: Redesign of the hierarchical planning framework for AWL

4.2.2 Hierarchical control levels

The hierarchical control levels are based upon the information provided in Table III.2 in Appendix III. Table III.2 shows different characteristics of the different levels of control at AWL and provides input for the redesign of the hierarchical framework. It indicates and verifies differences between the levels of control. Table III.2 distinguishes between the scope of the decisions made, the decision maker at the hierarchical level of control and the arising uncertainties. Based on the verification of experts, we have composed the redesign of the hierarchical framework tailored for AWL.

Strategic level

At the strategic level, decisions are made for all facilities of AWL, called the global organization. The horizon is currently two years. These decisions are of structural influence for the entire organization and should be based on highly aggregated data and forecasts. Furthermore, the decisions made at this level determine the relations for the underlying control level to operate in. For example, the capacity relations are fully flexible at this control level. AWL determines the number of employees that should be hired in order to fulfil the expected order intake. The number of hired employees determines the capacity availability for the tactical and operational level. The decision makers at this level of control are the board of directors. The type of uncertainty that occurs at this level concentrates on the occurrence of demand. The occurrence of demand influences all managerial areas since investments plans, accuracy of the long term demand forecasts, required warehousing space and inventory policies all depend upon the occurrence of demand.

Tactical *high level*

We observe that for one facility, called the local organization, we can distinguish between decisions regarding all projects or decisions regarding a single project. These type of decisions have different characteristics. For example, the level of detail of decisions for all running projects is more aggregated compared to decisions for a single project. Furthermore, the decision makers, the horizon of taking decisions and uncertainties are different. Details regarding these differences are mentioned in Table III.2 in Appendix III. We therefore choose to distinguish between a tactical *high level* and *low level* for AWL.

At the tactical *high level,* decisions should be taken for multiple projects at one facility. We can distinguish between different segments (i.e. body, seating and special). However, the data for making decisions at this level should be highly aggregated and based on forecasts in combination with actual demand. Decision makers at this level are the sales department, the tactical planners, the managing director NL and the managers of the different departments at AWL NL.

Uncertainties that may appear at this moment in time are the moment an order is received and the final result of the negotiation process. Besides, the capacity availability for each segment is unsure and hard to estimate.

Capacity is flexible on temporal basis. This means that extra capacity could be hired in advance, for example several weeks in advance, for an entire period, let's say two months. Temporal capacity expansions should be based on demand and supply forecasts. If the company expects a higher workload for several months a year based on historical data, AWL could hire extra temporary employees for that period.

Tactical *low level*

At the tactical *low level*, decisions should be made regarding a single-project based on actual demand. The data is still aggregated, because it concerns a project as a whole.

Important stakeholders at this level are account managers of the sales department who are responsible for acquiring a new order. Tactical planners are still responsible at this level for planning an entire project based on aggregate information. Team leaders are responsible for providing insight in the capacity availability of the assembly and engineering department.

Additional capacity can be hired on temporal basis at this level. Because the horizon of the tactical *low level* should have the length of at least one project cycle, which is 9 months, it is possible to hire additional capacity in advance for a longer period of time.

Uncertainties concern the exact work content and precedence relations of the project activities within the project. These aspects are uncertain in this project phase since the negotiation phase is not finished.

Operational *offline*

At this level of control, short-term decisions are made. This level addresses the detailed planning that is made two weeks before the start of the assembly phase. Uncertainties that occur at this level are material availability to start an operational activity and the mistakes that are made earlier in the process. Decision makers are the operational planners who are responsible for planning operators and engineers in the future. Project coordinators, operators and engineers are stakeholders since they are scheduled at this level. Capacity is flexible on incidental basis. For example, capacity becomes available because operational activities are delayed. Furthermore, it is still possible to hire additional capacity some days before the start of an activity, at higher costs.

Operational *online*

This control levels deals with unforeseen issues. Examples of unforeseen issues are rush ordering at the welding department, or illness of a programmer. Unforeseen issues are called 'out of control' issues at AWL. Operational planners are the decision makers at this control level and discuss 'out of control issues' with the manager operations. At this level of control, capacity is seldom flexible, since resources are already allocated at the operational *offline* level. Since the issues at this level are all unforeseen, decisions can only be made at a *reactive* basis, meaning that operational planners have to react after the incident. It is therefore important to monitor the process in order to deal with these unforeseen events.

4.2.3 Managerial areas

The framework distinguishes between four different managerial areas which are generic for the framework (Hans et al., 2012). We explain the most important key questions per managerial area at AWL.

Financial planning

This area focusses on the financial aspects of AWL, starting with a strategy plan and investment plan until cash flow analysis of a project at the operational *offline* level. Involved departments are the sales department, the financial department and the cost engineering department.

Examples of questions that involved business units at AWL should answer are:

- Strategic: what solvability percentage should we strive for?
- Strategic: is it cost effective to invest in new technologies?
- Tactical: what should the business plan for AWL look like?
- Operational: who solves the payment issues with customers?

Technological planning

The technological planning area concerns all technological information at AWL. The technological planning area is of high importance for AWL since engineering new solutions is one of the key activities of AWL. Activities in this area concern both the product and process design. Involved business units are: R&D, engineering and project management. Important questions for these departments are:

- Strategic: what new technologies should we develop?
- Tactical: what should the macro process plan for the different machine types look like?
- Operational: what are the precedence relations between different project tasks?

Resource capacity planning

This pillar concerns the capacity management of the entire organization. Capacity management is important for AWL, since on-time delivery to customers is one of the most important issues which is impossible without proper capacity management. Capacity management ranges from facility allocation till project scheduling and staff allocation. Long range forecasting and making a sales plan, facility management and human resource management are the most important activities in this pillar and are executed by the HRM, planning and assembly department of AWL.

- Strategic: what will be the expected demand for the coming year?
- Tactical: how much capacity do we need to meet the sales plan in the coming year per resource group?
- Operational: how can we allocate our resources in the most efficient way?

Material coordination

The material coordination pillar concerns the materials and other requirements to make the demand plan and product design plan possible. Most important activities are warehousing and inventory management at the strategic level. Furthermore, purchasing long lead time items and BOM items are also important activities. The involved business units are the purchasing department and the logistic department. Important questions to answer for these departments are:

- Strategic: what should or warehousing policy look like? How should our global supply chain look like?
- Tactical: what items should we purchase at a local level?
- Operational: how can we deliver material efficiently to assembly sub-assemblies as fast as possible?

4.3 Multi-project planning for AWL

Chapter 3 and Sections 4.1 and 4.2 show that the tactical planning function is currently overlooked by AWL. Based on this information, we zoom in on multi-project planning for AWL, since this lacking planning function is most in line with the core problem of this research. This section explains how AWL can plan multiple projects simultaneously. Multi-project planning should result in an overview in which lead times of activities of all projects are based on the available capacity. Multi-project planning is complex because AWL faces many uncertainties. Furthermore, the degree of variability is high because of the non-repetitive production characteristics. On the other hand, delivering orders on time is one of the key performances of an ETO organization (Olhager, 2019). In order to so, it is crucial that the organization has insight into the current utilization of resources while details regarding the project content or BOM are uncertain. In this section we explain how the problem of matching available and required capacity based on aggregate data for multiple projects simultaneously while occurring uncertainties can be tackled. We identify the characteristics of multi-project planning for AWL. Furthermore, we describe what is necessary to implement multi-project planning successfully in the future.

4.3.1 Introduction to multi-project planning for AWL

Multi-project planning for AWL should be a tactical planning function that offers the opportunity to extend capacity temporarily, in terms of working in overtime, hiring additional employees or subcontracting. The output should be a project plan with workload distributions based on project activities. An aggregate production plan for multiple projects will be helpful for management to identify possible gaps between capacity and demand. Aggregate capacity planning at the strategic level only considers projects as a whole, while scheduling at the operational level concerns detailed project data. Multi-project planning uses project activities. These activities consist of several underlying operational activities, called project tasks in this report. However, since the project trajectory is not known in advance, the project tasks are unknown at this stage of the project. Appendix II shows a practical example of multi-project planning.

Objective

Each level of control has its own objective and corresponding relations. Together they should support the overall planning process. In Section 2.2.2 we addressed that De Boer (1998) distinguishes between two approaches, either resource driven or time driven. In a time driven approach, due dates are hard and the aim is to minimize the usage of non-regular capacity. In principle, the customer dictates the project due date to AWL. However, the due date is negotiable if it is unrealistic for AWL. However, AWL strives to achieve the due date dictated by the customer, due to competitiveness. We therefore assume that a time driven approach is most appropriate approach for AWL. We formulate the objective for multi-project planning as follows: *"Minimize the variable costs of staff involved during the engineering and assembly process"*. The following costs should be included: i) personnel payroll, ii) overtime costs, iii) outsourcing costs, iv) subcontracting costs, v) costs hiring personnel. The costs per resource group may differ. For example, a robot programmer has a higher hourly rate than a mechanical technician. By setting this objective we expect that the usage of non-regular capacity reduces and the expected workload becomes more stable.

Constraints

Multi-project planning for AWL is restricted to several requirements, called constraints:

- The planning horizon should be divided into time periods of variable length. Multi-project planning should consider shorter time periods at the beginning of the planning horizon. The periods become larger as we advance in time. This is due to the fact that the accuracy of data is less detailed at a further period in time. We suggest to divide a year as follows: the first two months should be divided in weeks, because AWL has a high accuracy of data two months in advance. The remaining ten months should be divided in months.
- All project activities of an order should be completed in time, before the customer due date. Backlogging is not allowed.
- All project activities should be finished entirely.
- The project activities should respect the predetermined precedence relations.
- All project activities should be finished without pre-emption.
- The capacity usage should not exceed the available regular and non-regular capacity.

Uncertainties

AWL faces uncertainties on a daily basis. Uncertainties can have a devastating effect on the project performance.

- Negotiation: negotiation is a crucial step in the order acceptance phase. The outcome of negotiation is uncertain, since it depends on the competitiveness of AWL. In reality, we see that 50% of the orders are lost during the negotiation phase. The chance of losing an order is significant and it is therefore hard to make estimations regarding the required capacity during the order acceptance phase.
- Precedence relations: the project content is uncertain during the order acceptance phase and may change over time. This implies that the project trajectory and hence precedence relations, are uncertain. Furthermore, mistakes made earlier in the process cause several activities to start over again.
- Work content: the project content is not agreed upon by both parties involved during the order acceptance phase. The work content may change over time, which results in uncertainty for AWL.
- Staff availability: availability of regular and non-regular capacity are both a source of uncertainty. Availability of regular capacity depends on long-term illness of employees. Availability of non-regular capacity depends upon the possibility to hire additional staff, the willingness to work in overtime and the possibility to outsource activities. These aspects are hard to estimate in advance.

4.3.2 Input data

Input data is required to create a multi-project overview of all running projects. The first aspect is the planning horizon. Thereafter we explain the project activities, their corresponding precedence relations, milestones and the aspects of regular and non-regular capacity.

Planning horizon

Figure 4.3 shows that multi project planning is located at the tactical *high level*. According to Hax and Meal (1965), the total time horizon that should be considered must be long enough to cover at least one cycle of all the products involved. On the other hand, it should be short enough to make the model computationally feasible and to allow demand forecasts to be reasonably accurate.

A rolling planning horizon of one year will be most appropriate planning horizon for multi-project planning. The cycle of one project takes nine months on average, in the meantime new projects are accepted or in the pipeline which implies that a longer horizon is required. We therefore think that a rolling planning horizon of one year is sufficient. The term rolling horizon refers to revising or updating an existing forecast for decision making. So, the term 'horizon' refers to the period in the future for which a forecast should be made, that gets 'rolled over' every month.

Milestones

At AWL, the customer dictates the project due date. This implies that this date is not negotiable, unless the project due date is unrealistic. Furthermore, the customer dictates several 'customer milestones'. The customer wants to be certain that these milestones can be accomplished by AWL. These milestones function as input for multi-project planning. These milestones are: project start, pre-acceptance and final acceptance.

Project activities, minimum duration and precedence relations

The project activities that have to be executed function as input data for multi-project planning. Every project trajectory consists of the same project activities, however the workload per project activity may differ. The possibility to outsource or hire additional staff depends upon the project activity. For the engineering department, it is possible to outsource mechanical engineering activities for jigs to MechDes, a subsidiary of AWL. Simulation engineering can sometimes be outsourced to external companies. Hardware and fluid engineering activities can be outsourced to Aartec Engineering B.V., an external company. For the assembly phase, it is possible to outsource the base assembly and the encasing assembly.

<u>Engineering</u>

The engineering department designs machine aspects. For more details we refer to Section 3.1.2. We distinguish between eight project activities. All activities have a minimum duration, require different resources and are restricted to precedence relations. The minimum duration is hard to estimate. However, the duration cannot be less than the workload of administrative tasks, which takes at least 8 hours. For smaller projects, the minimum duration of mechanical engineering – *cells* cannot be less than 240 hours. This is due to the fact that mechanical engineering of a small project can be executed by only one engineer. Furthermore, the subsequent steps require agreements with the customer. This takes at least six weeks for one engineer. For larger projects, the minimum duration of mechanical engineering – *cells* takes at least six weeks as well. However, it is possible to work with two engineers for larger projects.

The number of employees that can work on the project activity simultaneously depends upon the Work Breakdown Structure (WBS) per project. The team leader of the engineering departments determines for every project the number of engineers per project activity, based upon the WBS. The numbers of employees in the column "Max employees per activity" is determined together with the manager engineering.

Table 4.1 displays the different activities and the corresponding resource groups, the possibility to hire additional staff or outsource this activity and the minimum and maximum number of employees that can work on this activity simultaneously.

Project activity	**Resource group**	**Possibility for hiring or outsourcing**	**Min employees per activity**	**Max employees per activity**	**Minimum duration (h)**
Mechanical engineering - *cell*	Mechanical engineers	Outsourcing to MechDes and hiring	1	15	8 – 240/480 (small/large projects)
Mechanical engineering - *moulds*	Mechanical engineers	Outsourcing to MechDes	1	10	8 – 150/300
Simulation engineering	Robot simulation engineers	Outsourcing to external company and hiring	1	3	8 – 50/100
Process engineering	Weld and process engineers	Hiring	1	2	8 – 100
Control Safety	Safety engineers	Hiring	1	1	8 – 100
Hardware engineering	Hardware engineers	Outsourcing to Aartec and hiring	1	4	8 – 100
Fluid engineering	Hardware engineers	Outsourcing to Aartec and hiring	1	2	8 - 100
PLC engineering	PLC engineers	Hiring	1	3	8 – 240/480
Robot engineering	Robot control engineers	Hiring	1	4	8 – 120/240

Table 4.1: Characteristics engineering process

Figure 4.4 visualizes the precedence relations between the different activities.

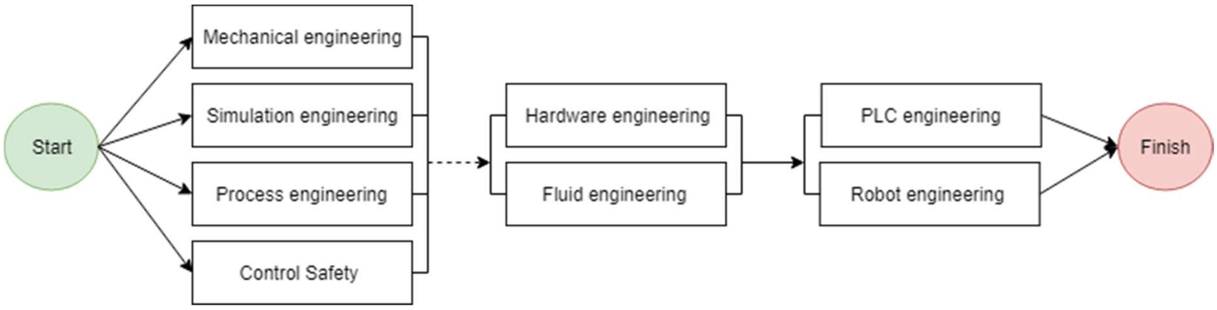

Figure 4.4: Precedence relations engineering phase

The dotted arrow in Figure 4.4 indicates a different precedence relations. The dotted arrow indicates feeding precedence relation while the solid arrows indicates finish-to-start precedence relations. Hardware engineering and fluid engineering can start when the previous four activities are completed for at least 2/3 part. The last two activities can only start when all the previous activities are completed.

<u>Nominal assembly</u>
During the nominal assembly phase mechanical and electrical aspects are fulfilled. After the nominal assembly, the machine is assembled but not functioning yet. For more details, we refer to Section 3.1.4.

AWL wants to work with sub-assemblies in the future. These sub-assemblies are generic for machines. However, the composition of sub-assemblies per machine differs. All sub-assemblies require mechanical and electrical activities. The rationale behind the sub-assemblies is that different sub-assemblies can be assembled parallel which should save throughput time, if the available capacity is sufficient. The sub-assemblies function as project activities, since the sub-assemblies consists of several operational tasks which have to be scheduled at the operational level.

Table 4.2 shows the different activities (sub-assemblies) and the required resource groups, the possibility to outsource the activity or hire additional staff and the minimum and maximum employees that can work on this activity.

Figure 4.5 visualizes the precedence relations of the nominal assembly phase. Sub-assemblies can be assembled in parallel, but also sequentially. However, due to operational restrictions mechanical technicians should start before electrical technicians. The mechanical technicians have to complete the activity for at least 1/3 before the electrical technician can start their work. Feeding precedence relations are therefore required between mechanical and electrical activities. Feeding precedence relations are indicated by the dotted lines in Figure 4.5.

Project activity	**Resource group**	**Possibility for hiring or outsourcing**	**Min employees**	**Max employees**	**Min duration mechanical (h)**	**Min duration electrical (h)**
Base assembly	Mechanical and electrical technicians	Hiring and outsourcing	1	2	16	24
Encasing assembly	Mechanical and electrical technicians	Outsourcing	1	2	16	8
Indexer assembly	Mechanical and electrical technicians	Hiring	1	3	16	24
Media service assembly	Mechanical and electrical technicians	Hiring	1	1	32	16
Operator assembly	Mechanical and electrical technicians	Hiring	1	2	8	8
Process assembly	Mechanical and electrical technicians	Hiring	1	1	8	4
Robot assembly	Mechanical and electrical technicians	Hiring	1	2	16	8
Add-ons	Mechanical and electrical technicians	Hiring	1	1	16	16

Table 4.2: Characteristics nominal assembly

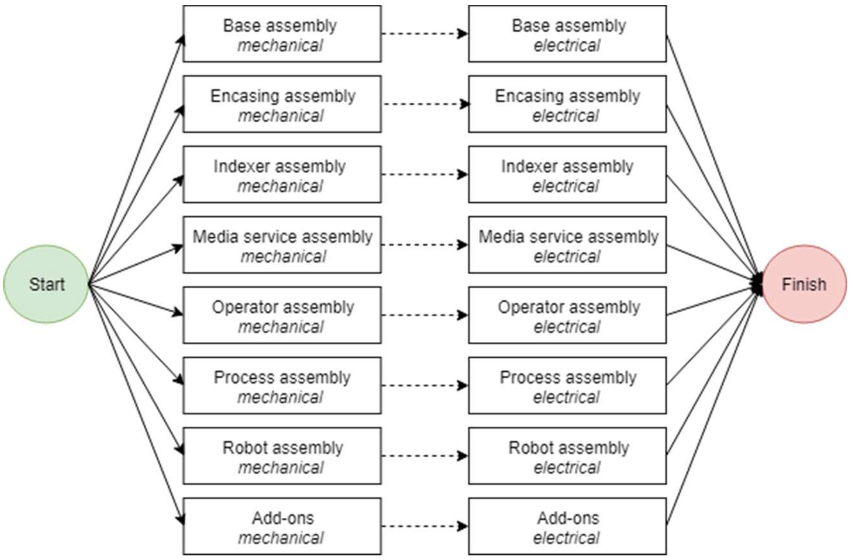

Figure 4.5: Precedence relations nominal assembly phase

Nominal commissioning

Software has to be installed on the machine hardware in order to make the machine operational. During the nominal commissioning phase, the software installation is prepared. We make a distinction in this phase since the required resources group is different than the resources of the nominal assembly phase. The activities of this phase have to be fulfilled with one or two employees. That is why we did not make a distinction between the minimum or maximum number of employees working on an activity.

Project activity	**Resource group**	**Possibility for hiring or outsourcing**	**Required number of employees**	**Min duration (h)**
IO testing	PLC programmer	Hiring	1	16
Commissioning PLC program	PLC programmer	Hiring	1	40
Commissioning Robot program	Robot programmer	Hiring	1	40
Commissioning process equipment	Welding technician	Not possible	1	40
Machine safety check	PLC programmer, safety engineer	Hiring	2	5

Table 4.3: Characteristics nominal commissioning

The precedence relations are visualized in Figure 4.6. The activities placed under each other can be executed in parallel. The other activities can only start when the previous activities are completed (i.e. finish-to-start precedence relations).

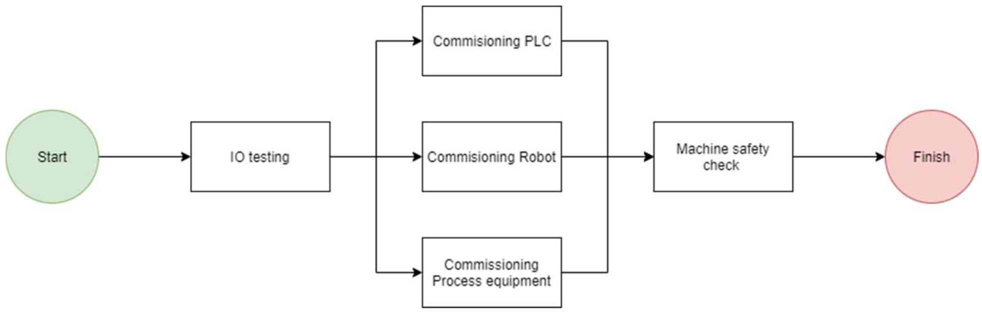

Figure 4.6: Precedence relations functional assembly phase

Functional assembly

AWL defined a separate assembly phase for installing the software on the machine, called the functional assembly phase. The process is described in more detail in Section 3.1.4. The project activities, the required resources, the possibility to hire or outsource the activity and the required employees for executing the activity are displayed in Table 4.4. In the functional assembly we can only work with one employee at an activity.

Functional assembly	**Resource group**	**Possibility for hiring or outsourcing**	**Required number of employees**	**Min duration (h)**
Integrate fixture (moulds)	PLC programmer	Hiring	1	16
Teach robot paths	Robot programmer	Hiring	1	24
Execute test plan	PLC programmer	Hiring	1	80
Support functional testing	Robot programmer	Hiring	1	80

Table 4.4: Characteristics functional assembly

The precedence relations are visualized in Figure 4.7. The last two activities should be executed in parallel. The other activities are connected via finish-to-start precedence relations.

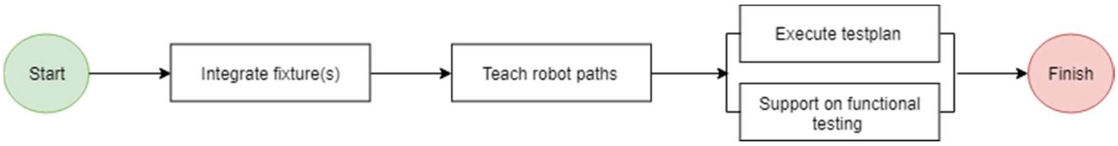

Figure 4.7: Precedence relations functional assembly phase

Availability of staff

This section explains aspects of regular and non-regular capacity of the resource groups. The availability of staff is important input data for multi-project planning, since the production plan is made against finite capacity.

Regular capacity

The regular available capacity consists of the amount of FTEs. The previous section identified 12 different resource groups. Table 4.5 shows the current regular available capacity, which is based on an average number of FTE available in 2019. Structurally hired FTEs are not counted in this table.

Non-regular capacity

AWL has three options to work with non-regular capacity: 1. Outsource activities, 2. Hire staff on a temporarily basis and 3. Working in overtime.

The possibility of outsourcing depends upon the activity. We therefore indicated the possibility for outsourcing in the previous tables. The second option is hiring additional staff. This option is often used and possible for almost all resource groups. The hired capacity given in Table 4.5 is based upon the number of hired FTEs at this moment in time, since the amount of hired staff is changing frequently over time. AWL does not make a distinction between structurally hired staff and incidentally hired staff. The time period in which AWL can hire additional staff depends upon the resource group. However, in case of a rush order, it is possible to hire employees one day in advance.

Resource group	Regular capacity (FTE)	Hired capacity (FTE)	Term of hiring staff
Mechanical engineers	16	2	Per week
MechDes engineers	41	0	Per week
Robot simulation engineers	8	0	2 months
Weld and process engineers	6	0	No hiring on short term
Control engineers	13	3	2 months – 2 weeks before the start
Safety engineers	5	1	No hiring on short term
PLC engineers	17	4	No hiring on short term
Mechanical technicians	26	3	2 weeks in advance - daily
Electrical technicians	10	7	2 weeks in advance – daily
PLC programmers	11	5	2 weeks in advance – daily
Robot programmers	17	8	2 weeks in advance – daily
Welding technician	10	1	No hiring on short term

Table 4.5: Characteristics regarding capacity

Working in overtime is used when milestones are not completed in time. It is possible for all resource groups to work in overtime.

4.3.3 Output data

This section describes the output data of multi-project planning. We discuss the practical output data of multi-project planning. Thereafter we explain the kind of decisions that can be made with output of multi-project planning and the involved stakeholders that should make these decisions.

Costs

The aim of multi-project planning is to roughly match available capacity with demand according to the objective function: *"Minimize the variable costs of staff involved during the engineering and assembly process"* while respecting the corresponding relations. Multi-project planning should result in a production plan with workload distributions per resource group for all incoming and already committed projects along the planning horizon and their corresponding costs. It should be possible to create several scenarios for accepting or rejecting a new order and see the corresponding costs of these different options. This information could be used during the order acceptance phase.

Milestones

In Section 4.3.2 we explained that the customer dictates several milestones to AWL. Next to that, AWL creates milestones to monitor the progress of the project. A multi-project overview should enable to see whether a project is on schedule, delayed or ahead, with the aid of milestones. Per project, the start time, completion time of a project activity and project milestones should be indicated in the project plan, based on the available capacity.

Project milestones that should be output of multi-project planning are as follows per project:

Engineering

- Concept freeze
- Design freeze
- Release for production

Assembly

- Kick-off assembly
- Nominal ready
- Functional ready
- Pre-acceptance
- Final acceptance
- Project due date

Duration of a project activity

The duration of an activity in the project plan is not fixed. The duration depends on the workload and availability of staff per resource group. However, the duration cannot be less than the minimum duration. The duration should be indicated by the means of a start- and completion time per project activity.

Required capacity

The output of multi-project planning should provide insight into the usage of regular and non-regular capacity per resource group per moment in time. This information can help managers of the engineering and operations department to hire staff in advance on a temporarily basis.

The output data per project can be summarized as follows:

- Staff costs of different scenarios
- Milestones per project
- Start time of an activity
- Completion time of an activity
- Required capacity of a specific resource group per point in time, divided in regular and non-regular capacity

Possible decisions and stakeholders

Multi-project planning should assist tactical planners in making a plan for a single project. Internal and external due dates and delivery times depend upon the capacity usage of running or already committed projects. By doing so, the internal and external due dates and delivery times will be based upon the actual workload and the available capacity which prevents an overloaded system. The sales department should use this information during the order acceptance phase. Insight in the resource utilization should indicate whether it is wise to accept or reject a new order. The objective function can be used to estimate the additional costs of accepting demand.

The manager director wants to be informed about demand peaks in a specific period. In this case, an estimation can be made for the importance of incoming demand and rush orders. Subsequently, it should be decided whether it wise to hire additional staff, discuss possibilities to postpone or reject the demand.

Information that becomes available by multi-project planning should enable early recognition of capacity deficits. As a result, other departments have to act at an earlier point in time than is currently done. For example, HRM can be involved at an earlier point in time to hire additional staff for a temporal or even structural period. This is currently impossible, because the project information that is currently available is too limited to take these decisions.

4.4 Interaction and integration

The previous sections made clear that multi-project planning provides insight in the progress of multiple projects and the corresponding utilization of resources. This insight can be used as decision aid for stakeholders. Interaction and integration between different departments and levels of control is required to implement multi-project planning successfully throughout the entire organization.

4.4.1 Design of the tactical planning meeting

Section 4.1.3 explained that there is no interaction with the tactical planning level. We therefore suggest to start a tactical planning meeting that should play a crucial integrative role between different departments and the strategic and operational level respectively. We design the information flow for this meeting. The purpose of the meeting is to gather the required input data for multi-project planning, establish lead times for incoming projects and discuss the possibility to accept more orders based on the current resource utilization. We explain the information flow and the progression of the meeting, the frequency and decisions made during this meeting.

Design, frequency and decisions

Figure 4.8 shows the information flow of the meeting, based on provided information in Table IV.1 in Appendix IV.

The planning horizon of the tactical *high* level is 12 months. We therefore suggest to organize this meeting every month. The meeting should proceed as follows. The tactical planner(s) should provide a multi-project view during the meeting with actual status of running projects. The overview should be based on actual information of already required orders in combination with a demand forecast for the entire planning horizon. Based upon the sales forecast the tactical planner should give insight in the load profiles, utilization for the different resource groups.

The sales department should provide actual information regarding incoming production orders. The manager of the operations and engineering department provide insight regarding the actual resource utilization.

The tactical planner uses the actual information to refresh the multi-project view for the next meeting and is able to provide advice to the salesmen on order acceptance or rejection of the new incoming orders. The managers of the engineering and assembly department are able to make decisions regarding temporal capacity expansions.

The managing director uses information regarding resource utilization for decisions concerned with structural capacity expansions and incoming rush orders.

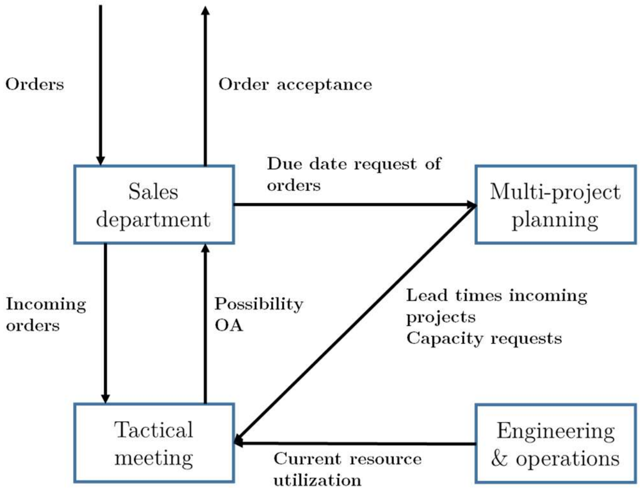

Figure 4.8: Information flow during the tactical planning meeting

4.4.2 Interaction with other levels of control

The previous section mainly explained the horizontal interaction with other business units. However, vertical integration is also important for enrolling multi-project planning successfully. We explain our suggestions for the interaction for the strategic and operational planning level respectively.

Strategic planning level

The managing director is the stakeholder that is responsible to interact with the board of directors at the strategic planning level. The managing director should announce the target order intake for AWL NL during the tactical meeting. Based upon the actual performance of the production system, the managing director is responsible for providing feedback to the board of directors. We suggest that the managing director should exchange the following information to the board of directors at the strategic level:

- The actual order intake per segment YTD (i.e. body, seating or special)
- The sales forecast for the entire planning horizon of the tactical *high* level
- The utilization of the engineering and assembly department

After exchanging this information for three months, the board of directors summarize this information and base the quartile update upon this information. By doing so, the output of the tactical planning meeting functions as input for the quartile update.

Operational planning level

The managers of the engineering and operations department are responsible for the interaction with the operational *offline* level. Both managers are responsible for sharing the obtained information with the team leaders and operational planners of the engineering and assembly department. We suggest exchanging the following information:

For the operational *offline* horizon (2 – 8 weeks):

- Per incoming order:
    - Segment of order (i.e. body, seating or special)
    - Machine type (arc welding, laser welding, spot welding)
    - Customer due date of the order
    - Proposed start- and completion time of aggregated engineering activities
    - Proposed start- and completion time of the aggregated assembly activities
    - Estimation of required capacity per resource group

This information should function as input for the operational weekly meeting. The frequent exchange of information should integrate the managerial areas and the different levels of control. We expect that this information exchange results in a production system that is better prepared for incoming orders. At the end, this will result in less 'fire-fighting' of operational managers, team leaders and operational planners at AWL.

4.5 Conclusion

This chapter showed a practical application of the hierarchical planning framework of Hans et al. (2005). This chapter emphasized the following aspects:

- We applied the current situation of AWL on the hierarchical planning framework of Hans et al. (2005).
- We identified absent planning functions and concluded that the tactical planning level is poorly addressed by AWL.
- We redesigned the content of the planning framework tailored for AWL.
- We zoomed in on the multi-project planning function for AWL.
    - We explained what multi-project planning should look like for AWL.
    - We explained the required input and output data.
    - We explained how the interaction between departments and different planning levels of control should look like.
    - We introduces a tactical planning meeting and explained the information flow and progression of this meeting.

First, we applied the current situation of AWL and showed the content of the planning framework in Section 4.1. Based on this view, we were able to identify absent planning functions. We concluded that the tactical level is currently poorly addressed by AWL.

Chapter 5: Roadmap towards improvement

This chapter constructs a step-by-step implementation plan for multi-project planning at AWL. The first step is gathering the required planning data, which is the focus of Section 5.1. In Section 5.2 we concentrate on the second step: the required organizational changes. The last step is software support. In Section 5.3 explains how software should support the tactical planning function. This section describes the software requirements and verifies whether the current planning tool: MS projects, is able to meet those requirements. Paragraph 5.4 gives a recommendation regarding a tactical planning algorithm.

5.1 Improve quality of data

This section discusses the data that is required for implementing multi-project planning. Currently, some required input data is missing or unreliable. The quality of input data of multi-project planning has to be improved in order to make multi-project planning successful.

Identify the minimum duration per project activity

In Section 3.2.2 we explained that there is currently no buffer visual in the project plan. This is due to the fact that tactical planners plan longer lead times than the actual workload in order to create slack. Since the minimum duration is input data for multi-project planning, we advise to identify and map the minimum duration per project activity. We observed that the minimum duration of a project activity depends upon the welding process used. For example, the assembly process of a laser welding machine is more complex than an arc welding machine. The minimum durations for some project activities of a laser welding machine are therefore larger. We advise to take this observation into account and identify the minimum duration of project activities per welding process.

Identify and map precedence relations

Currently, precedence relations are not specified in a project plan. The tactical planners know relations between different project activities by heart and plan them accordingly. This is negative for the quality and reliability of the project plan. Manual adjustments could cause mistakes. Since the project plan is a large file, it is easy to forget an adjustment. Mapping precedence relations in MS projects makes it possible to adjust the successive project activities in the project plan automatically if one predecessor changes.

In Section 4.3 we distinguished between finish-to-start and feeding precedence relations. It is important to make a clear distinction between the different kind of precedence relations within the project plan. AWL should identify and define a percentage of the workload that has to be performed before the next project activity can start for all overlapping activities. The overlapping activities were indicated in Section 4.3.2, percentages for overlapping activities were also given for the Basic Spot machine.

Define the maximum number of employees working on a project activity

Important input data for multi-project planning is the maximum number of employees that is allowed to work on the same project activity simultaneously. This data is currently not available at AWL. We therefore advise to define this data for the different project activities explained in Section 4.3.

Improve data regarding milestones

Milestones should be used to monitor the progress of projects. However, the data that is currently used regarding milestones is unreliable. Employees do not see the urge to enter correct milestone data in the system. Milestones are seen as a guideline, instead of a due date. In addition, employees sometimes alter the milestone information in the system, when milestones are not completed on time, which is misleading. We therefore suggest to emphasize the importance of entering reliable milestone data in the system.

Define the available regular and non-regular capacity availability per resource group

Assuming infinite regular and non-regular capacity is unrealistic. We therefore advise to define the available regular and non-regular capacity per resource group. In the capacity plan that AWL currently uses, a distinction is made between three resource groups: engineering, programming and assembly. In Section 4.3 we identified twelve different resource groups at the tactical level. We recommend to distinguish between these twelve different resource groups. Furthermore, the manager engineering and manager operations should make agreements with the tactical planner regarding the amount of regular and non-regular capacity that can be used in a certain time period. This information serves as input for multi-project planning and can be used during the order acceptance phase to determine whether a new order can be accepted or not, such that an overloaded system is prevented.

Make agreements upon the maximum utilization per resource group

In Section 3.2.2 we explained that the current utilization is aimed at 95% or higher for the operational process. This is extremely high for an operational process. For multi-project planning we advise to make agreements upon the maximum allowed utilization per resource group. This information can also be used during the order acceptance phase and should prevent an overloaded system. Furthermore, estimations regarding utilization per resource group can indicate when extra capacity must be hired on temporarily basis.

5.2 Organizational changes

This section explains the required organizational changes that are necessary to implement multi-project planning. We start with how to create awareness and support for this change. Thereafter, we zoom in on the changing responsibilities of several stakeholders. Finally, we explain how the communication structure should change in order to make interaction and integration between stakeholders possible.

5.2.1 Create awareness and support

To implement multi-project planning successfully, the urge to adjust the current way of working has to be acknowledged by all stakeholders. Thereafter, support is needed for change. We therefore emphasize how to create awareness and support for implementing project planning.

Sections 3.4 and 3.5 show the urge of altering the current planning method. The next step is creating support for this change. We explain two ways of creating support for this change. First, we explain the general strengths, weaknesses, opportunities and threats of implementing multi-project planning. Thereafter, we explain the personal interest per stakeholder.

Strengths

- Multi-project planning enables creating a project plan based on the actual available capacity. This results in workload dependent lead-times. It is therefore possible to quote more reliable due dates to customers.
- A multi-project view and insight in the current capacity usage provides additional information for the sales department. New orders can be accepted based on the actual capacity usage. By doing so, an overloaded production system can be prevented.
- Implementing multi-project planning allows incorporating the disturbances in a project plan. The effect of disturbances, for example rush orders, unexpected delays or capacity shortage, becomes visible. Decisions can be made based upon a multi-project overview. This results in a more controllable process and other planning decisions can be made. Therefore, the operational process becomes more controlled. Incorporating the effect of disturbances on other projects is impossible with the current way of working.
- Multi-project planning results in less non-regular capacity usage. Less employees will have to work in overtime and less additional employees have to be hired.

Weaknesses

- Multi-project planning requires complex mathematical computations. This is impossible without the right software support. This software has to be bought, which requires an investment. Furthermore, training for getting familiar with the software requires an investment as well.
- The reliance upon an IT system increases, due to the complexity of multi-project planning. In addition, the reliance upon the employees that work with the system increases.

Opportunities

- Multi-project planning plans project activities in a more efficient way. This results in a more equally spread workload. As a consequence, the overall utilization of the production system can be increased.
- The more equally spread workload enables the possibility to accept more orders with the same amount of regular capacity.
- A multi-project view enables noticing capacity excess. It makes it possible to approach customers of AWL and offers the opportunity to assemble a project in a specific time period, for example at a lower price.

Threats

- Implementing multi-project planning is a time consuming and complicated process. If the implementation takes too long, the process might not be supported by the management anymore.
- Multi-project planning results in a more complex planning process. The current knowledge might be inadequate to work with the increased complexity of the planning process. Without the support of planners the implementation of multi-project planning is not successful.
- The order acceptance process changes with the implementation of multi-project planning. Accepting every order is no longer possible. The reward structure and performance measure per sales employee have to be changed. This might result in resistance of the sales department. This problem is described in Section 3.5.1.

- Multi-project planning requires several changing job descriptions (see Section 5.2.2). The changing job description and different responsibilities might result in resistance of employees.

Another way of creating support and engaging stakeholders in a change is emphasizing their personal interest. Table 5.1 shows the advantages and disadvantages per stakeholder.

Stakeholder	**Advantages**	**Disadvantages**
Board of directors	• Cost reduction of hiring additional staff and working in overtime • Higher customer satisfaction, because the quoted due dates are more reliable • Higher employee satisfaction, because workload is more stable and an overloaded system is prevented	• Investment in a new planning tool • Investment in training are required to get familiar with the new planning tool
Managing director	• Decisions regarding rush orders can be made on actual resource utilization • Possibility to increase overall utilization	-
Sales director	• Arguments for order acceptance are improved • More reliable due-date quotation • Lead time reduction per project	-
Manager operations, manager engineering	• Workload for engineers and assembly is more stable, this results in more controllability of the process • More milestones can be completed on time • Lead time reduction per project • Possibility to increase utilization • Lower costs of hiring employees and working in overtime	-
Tactical planner	• Multi-project view and decisions	• Increased complexity of function/job.
Operational planner	• Fewer manual adjustments are required, less “firefighting”	• The responsibility changes, since the job description of operational planners should change.
Team leaders	• Incoming workload is more predictable	-
Project coordinators	• Accuracy of operational plan increases	• The responsibility changes, since the job description of project coordinators should change.
Engineers	• Workload is more stable	-
Operators	• Workload is more stable	-

Table 5.1: Personal interest per stakeholder

5.2.2 Changing job descriptions

Implementing multi-project planning at AWL requires changing responsibilities and tasks of multiple functions. We discuss the change in responsibilities of the tactical planners, project coordinators and operational planners respectively. The changing job descriptions are partially based upon the information in Table III.2: the redesign of the planning framework in Appendix III.

Tactical planners

Section 3.2.2 explains the tasks that tactical planners fulfil in today's organization. We observe that tactical planners are no longer responsible for updating or revising the project plan after the handover to the project coordinator. We advise AWL to alter the responsibility of the tactical planners and let them be responsible for altering and revising the project plan during the entire assembly process. In addition, the tactical planning function becomes more important due to multi-project planning. A multi-project overview should be created. Tactical planners should become responsible for creating the multi-project view. Furthermore, tactical planners should create different possible scenarios if a project revision is required.

Tactical planners should have an advisory role towards the manager operations and manager engineering regarding temporarily capacity expansions. For example, if three projects run simultaneously, three project coordinators make an operational plan. Due to scarce resources, an activity in a project must be postponed for three weeks, or all projects have a delay of one week. In the current situation, project coordinators try to prevent delay for their own project, by reserving operators in advance. This may lead to inefficient resource allocation. In the future, tactical planners have to provide an advice based on a multi-project view.

Project coordinators

Project coordinators are responsible for making an operational plan. We advise AWL to shift the responsibility of making an operational plan to operational planners. Project coordinators should be responsible for coordinating the project and maintain contact with the customer. Operational planning activities should be performed by operational planners, because making a detailed project plan per project leads to suboptimal resource allocation.

Operational planners

The responsibility of operational planners increases. At the moment, operational planners are responsible for resource allocation and not for making a detailed schedule for projects. In the future, operational planners should become responsible for making the operational schedule. In other words, we advise AWL to rearrange and centralize the operational planning process. By doing so, resources could be allocated more efficiently.

5.2.3 Changing communication structure

In order to make multi-project planning successful, proper communication is of high importance. The different business functions and stakeholders have to exchange all required data on time on a frequent basis. At the moment, changing project activities are communicated instantly from the project coordinator towards the team leader. The team leader communicates the change during weekly operational meeting.

A multi-project view makes it possible to see the effect of disturbances. It becomes possible to take proactive decisions instead of reactive decisions. In order to communicate on a frequent basis, we recommend to implement the tactical planning meeting as explained in Section 4.4.

Section 4.4 explains how to setup this meeting. The involved stakeholders, the input and output data and the decisions that have to be taken during this meeting.

5.2.4 KPIs

The last organizational change is implementing and monitoring new KPIs to measure the progression and improvement of implementing multi-project planning. Table 5.2 presents multiple KPIs. It presents who the KPI is relevant to and why the performance of this KPI should improve. Furthermore, we try to indicate the impact of multi-project planning on this KPI. We indicate the impact with either: significant, moderate or little. It is hard to quantify this impact since multi-project planning is a conceptual idea. The KPI that is already measured is indicates with (*). We abbreviate multi-project planning to MPP in Table 5.2. Appendix V explains the KPI formulas.

KPI	**Stakeholders**	**Performance**	**Impact**
Customer satisfaction	Board of directors Managing director	The performance of this KPI *increases* because: 1. More reliable due dates can be promised towards customers 2. Less WIP because of workload dependent lead-times 3. Less mistakes because of less WIP, quality increases 4. More reliable due dates result in improved delivery performance	The improvement will be *little.* 1. Performance KPI increases because more reliable due dates can be quoted. 2. However, customer satisfaction depends upon other aspects (service, quality of the machine etc.)
Percentage of projects delivered on time	Board of directors Managing director Manager operations	The performance of this KPI *increases* because: 1. MPP results in workload dependent lead-times 2. Hence, more realistic due dates can be quoted towards customers 3. Therefore, the delivery performance can be improved	The improvement will be *moderate.* 1. The delivery performance improves through MPP. 2. However, customer due dates are already deadlines for AWL. So, AWL strives to deliver the project on time already.
Percentage of milestones completed on time (*)	Manager engineering Manager operations	The performance of this KPI *increases* because: 1. MPP results in workload dependent lead-times. 2. Hence, milestones are based upon these workload dependent lead-times. 3. As a direct consequence, the performance of this KPI increases.	The improvement will be *significant.* 1. Milestones are based upon workload dependent lead-times. 2. Improvement of this KPI is an indicator of the planning accuracy, which improves by MPP.
Percentage of hired capacity	Manager engineering Manager operations	This percentage *decreases* because: 1. MPP plans project activities more efficiently.	The improvement will be *moderate.* 1. MPP plans project activities more efficiently.

		2. Hence, less employees have to be hired.	2. However, AWL depends upon structural hiring of employees. 3. The current labour market makes it difficult to hire staff on a structural basis.
Percentage of working in overtime	Manager engineering Manager operations	This percentage *decreases* because: 1. MPP plans project activities more efficiently, based upon available capacity. 2. This results in a more stable workload. 3. The planned projects activities are based upon workload-dependent lead-times. 4. As a direct consequence, the overtime is required to complete the project activities.	The impact of MPP on this KPI will be *significant*. 1. Project activities are planned more efficiently. 2. Projects are planned based upon finite capacity. 3. Reliable due-dates are quoted towards customers 4. Less ad-hoc changes are required. 5. The workload will be more stable.
Percentage of deviation between booked and budgeted hours	Tactical planners Operational planners	This percentage *decreases* because: 1. MPP plans project activities based upon available capacity. 2. Less non-regular capacity is required. So, the deviation between the booked and budgeted hours decreases.	The impact of MPP on this KPI will be *moderate*. 1. Less non-regular capacity is needed because of MPP. 2. The planning accuracy (difference between booked and budgeted hours) will therefore decrease 3. However, the budgeted hours depends upon the quality of the estimations of cost engineers.
Number of revisions of the tactical plan	Tactical planners	This number *decreases* because: 1. MPP plans project activities more efficiently, against finite capacity. 2. Hence, this results in workload dependent lead-times 3. MPP tries to reduce the internal variability caused by the engineering and assembly process.	The impact of MPP will be *moderate*. 1. The accuracy of a tactical project plan increases by MPP. 2. However, the number of revisions depends upon external variability (e.g. rush orders) as well.
Number of revisions of the operational plan	Operational planners	This number *decreases* because: 1. MPP results in workload dependent lead-times. 2. Currently, project activities are not planned at all. 3. We therefore expect a more controllable operational planning process.	The impact of MPP will be *significant*. 1. MPP enables a more controllable operational planning process. 2. A detailed schedule should not be made in isolation anymore (see 5.2.2) 3. We therefore think that the impact of this KPI is *significant*.

Table 5.2: KPIs per stakeholder

5.3 Support of software

This section explains the third step of implementing multi-project planning. We expect that software support is required, due to mathematical complexity. Using new software involves a make-or-buy decision. We explain the advantages and disadvantages of both making the new software in house and buying the software from a supplier. Thereafter we explain the software requirements and investigate whether the current planning tool MS projects, is feasible for multi-project planning.

5.3.1 Make-or-buy decision

Acquiring new software is a make-or-buy decision. This decision has to be made by the board of directors. However, we can provide our insights by classifying the advantages and disadvantages for this decision. A precondition for a make decision is the required mathematical- and programming knowledge. AWL has to assess whether the required expertise is currently available. We list the advantages and disadvantages in Table 5.3.

Decision	Advantages	Disadvantages
Make decision	Knowledge of algorithm is in-house Tendering process is unnecessary	Success is uncertain, due to mathematical complexity (lack of expertise) Dependency upon AWL programmer increases
Buy decision	Quality of tool is (probably) higher, since external company is specialised in developing planning software. Required changes in tool can be made by an external company, this an advantage for AWL since the activity can be outsourced.	Investment in a tool and training is required It is hard to find a supplier for a ‘tactical’ planning tool, most available tools are operational scheduling tools

Table 5.3: Advantages and disadvantages of the make-or-buy decision

5.3.2 Software requirements

Independently of the make-or-buy decision, requirements of software must be formulated. We explain the requirements and considerations regarding implementing tactical planning software. We make a distinction between technical and general software requirements.

Technical requirements

The first requirement represents the main idea of multi-project planning. The planning tool must support the planning of multiple projects simultaneously against finite capacity. By doing so, the software should provide actual insight in the progression of projects. It must be visible whether a project is on schedule, behind or even ahead of schedule. Furthermore, the current resource utilization per resource group should be visible.

A tactical planning tool should be able to show the consequences of various decisions. For example, during the order acceptance phase, the tactical planning tool should show the effect on the regular and non-regular capacity. Furthermore, making a plan is not a one-time event. It requires several revisions. Therefore, it should be possible to update the plan easily.

Section 4.3.1 explains the uncertainties that AWL faces. Ignoring these uncertainties leads to unrealistic assumptions. We therefore recommend to invest in a tool that can take uncertainty into account. Taking uncertainty into account results in a robust plan. A robust plan implies that the plan is as insensitive to uncertainty as possible. Uncertainties that a tool should take into account are: negotiation, work content and staff availability. We leave the uncertainties regarding precedence relations out of scope. The project activities are generic for most projects. Negotiation could be modelled in the tool by adding a stochastic parameter whether the order may occur or not. The work content could be uncertain and vaguely described by experts; for example, planners estimate that robot programming requires on average 100 hours, but in extreme cases this may be 200 or 60 hours. The model should be able to take these possible cases into account by modelling different scenarios. Staff availability could be modelled by planning against different percentages of available staff. For example, the tool should be able to generate a plan where 100% of the staff is available, or just an availability of 80%.

The tactical planning tool should be integrated with the operational planning tool, the AWL-planner, and the ERP system, Navision. It is unlikely that AWL buys a new operational and tactical planning tool at the same time. We therefore put emphasis on the requirement that these three systems have to be integrated and have to work together. The ERP-system ensures the input data for multi-project planning. The AWL-planner can be used for resource allocation.

General requirements

User friendliness is an important general requirement. Multiple stakeholders should have access to the tool for example: tactical planners, IT and project managers. The software should be easy to work with for all stakeholders. Graphical aspects of the software should support a high level of understanding of the tool, since different stakeholders have to work with the software. AWL requires different user rights granted to them. Furthermore, it should be possible to work in a multi-user environment.

5.3.3 Feasibility of MS Projects

Tactical planners use Microsoft Projects (MS Projects) to make a project plan. We compare the functionalities of MS Projects and MS Projects Server. MS Project is a project management tool that can be used to create a clear oversights of projects, based on a time scale and resource usage. MS Projects Server is a project management server which stores project information in a central SQL Server database. At the moment, AWL only has a license for MS Projects. Information regarding central project information is not collected yet. Table 5.4 lists the requirements and checks whether the tool is able to fulfil the requirements of a tactical planning tool.

MS Projects and MS Projects Server are both able to create a multi-project view and to show critical resources when multiple projects use the same resources. In addition, different types of precedence relations can be modelled. MS Projects is not a planning tool. It is impossible to have automatic updates of a plan due to disruptions.

Requirement	MS Projects	MS Projects Server
Create multi-project view	X	X
Actual insight of resource utilization per resource group	X	X
Plan multiple projects against finite capacity		
Update / revisions should be possible		
Provide insights in actual progression of projects	X (manual tracking)	X (manual tracking)
Simulate what-if scenarios		
Take uncertainty into account	X (by inserting a buffer)	X (by inserting a buffer)
Show effect on regular and non-regular capacity		
Incorporate different precedence relations	X	X
Integration with ERP-system and AWL-planner		X
User friendly	X	X
Graphical support	X	X
Different administrator rights per user		X
Multi-user environment		X

Table 5.4: Requirements for tactical planning tool

AWL is currently not using the possibility of MS Projects to create a multi-project view. Furthermore, AWL does not use the resource sheet possibility of MS Projects. Currently, AWL performs a capacity check retrospectively in the operational plan tool, the AWL planner. We advise AWL to create a multi-project view based on the project activities mentioned in this research and add the availability of twelve resource groups to a resource sheet in MS Projects. In this way, scarce resources are indicated based on a multi-project view. By doing so, AWL is not planning against finite capacity since MS Projects is not a planning tool. However, we do expect an improvement compared to the current way of working.

The following steps have to be taken to create a multi-project view:

- Make a single project plan in a separate MS Project file for every project with project activities explained in Section 4.3.2.
- Make a resource pool in a separate MS Projects file. Enter the available FTEs for the different resource groups distinguished in Section 4.3.2.
- Make “Masterproject” file and insert all single project plans via the button “Subproject”.
- Insert the resource pool in the “Masterproject” file, via the button “Share resources”.

In this way, MS Projects creates a multi-project overview and shows the critical resources. MS Projects is able to reschedule project activities to an another point in time when the resources are available.

The advantages are that a multi-project view is created, critical resources are identified and MS Projects reschedules project activities. The disadvantages are that MS Projects requires manual adjustments, the resource pool requires updates by team leaders. Another disadvantage is that MS Projects is only able to reschedule activities to a later point in time. Hence, MS projects does not plan activities in an efficient way.

MS Projects Server is able to store the information regarding multiple projects in a separate database. This speeds up the process. Furthermore, it is possible to work in a multi-user environment, so team leaders can update the information in the resource pool sheet.

5.4 Proposing a planning algorithm

Section 5.3.3 showed that improvements can be made with MS Projects. However, MS Projects is not a tactical planning tool. This section discusses the usefulness and suitability of the algorithms discussed in Section 2.3 for AWL. First, we explain the prerequisites of the algorithm. Subsequently, we propose a planning algorithm that suits AWL in the best possible way.

5.4.1 Requirements for the algorithm

AWL faces uncertainty on a daily basis. According to Wullink (2005), assuming deterministic input data and ignoring uncertainty results in an unreliable and nervous plan. We therefore advise AWL to implement a tactical algorithm as a planning tool that is able to take uncertainty into account. Two different approaches can be used for modelling uncertainty. These approaches are either pro-active or reactive. A pro-active approach takes buffers or statistical knowledge of uncertainty into account. An example of a proactive approach is using stochastic variables (i.e. Wullink 2005) or using fuzzy variables (i.e. Masmoudi et al. 2005). Deterministic models incorporate buffers to deal with uncertainty. A reactive approach revises or re-optimizes a schedule when unexpected events occur.

The second requirement of the algorithm is the possibility to incorporate different precedence relations in the algorithm. The algorithm should make a distinction between finish-to-start and feeding precedence relations.

The third requirement of an algorithm is the possibility to take variable time buckets into account. We observed that AWL has less detailed data regarding projects at a further planning horizon. Assuming that the accuracy of data is the same for all periods, in other words, dividing the planning horizon into equal lengths is therefore an unrealistic assumption. We suggest selecting an algorithm that has the possibility to use smaller time periods for the first two months, for example weeks, because more detailed information is available for the first two months. Use larger time periods remaining planning horizon, for example months.

Lastly, we suggest that AWL chooses an algorithm that is developed and useable for practical application. Several algorithms are developed to contribute to literature rather than a practical implementation. Algorithms developed especially to contribute to literature are complex and the practical usefulness for AWL of these algorithms is therefore questionable. Furthermore, some algorithms are not suitable for a large problem instance. For example, the model proposed by Cherkoui et al. (2015) is only useful if there are less than 60 activities. The usefulness in a practical application is linked to the computational time of an algorithm. Since the proposed algorithms are all exact algorithms, we have to look at possibility to solve the problem within polynomial time or the possibility to approach the solution by using a heuristic.

The mentioned requirements of an algorithm result in an accurate model. However, taking these preferences into account results in a complex mathematical model. There is always a trade-off between model complexity and its accuracy. This trade-off must be considered during the tendering process of the tactical planning tool.

5.4.2 Suggestion for an algorithm

Table 5.2 verifies whether the proposed algorithms of Section 2.3 comply with the prerequisites set in Section 5.4.1. Based upon Table 5.2 we conclude that the algorithms proposed by Wullink (2005), Carvalho et al. (2015) and Cherkoui et al. (2015) fulfil three out of the five preferences.

The goal of the algorithm of Carvalho et al. (2015) is to decrease the gap between literature and practice by developing an algorithm for a specific practical application. Since the proposed model in this paper focuses on the practical application, it is too specific to be applicable at AWL. We therefore do not take this algorithm into consideration. The algorithm proposed by Cherkaoui et al. (2015) is only applicable for a medium problem instance. The algorithm of Wullink (2005) is especially developed for ETO organizations that face uncertainty. We therefore propose the algorithm of Wullink (2005).

The algorithm of Wullink (2005) is an exact algorithm. Kis (2004) proves that the deterministic multi-project planning problem is *NP-hard in the strong sense*. NP-hard, Nondeterministic Polynomial, implies that the problems in this class cannot be solved to optimally in polynomial time. To provide a feasible solution to an NP-hard problem, heuristics are required that find a solution as close to the optimal solution. The complexity of the model of Wullink (2005) increases since uncertainty is added to the model. The computational time for solving increases exponentially by adding different scenarios. The model might become unattractive due to the many possible scenarios. Computational experiments show that significant improvements of the expected costs can be achieved by using a scenario based model, compared to using a deterministic model (Wullink, 2005). To speed up the computational process, Wullink (2005) proposes several heuristics. He distinguishes between constructive and improvement heuristics. Furthermore, Wullink (2005) proposes a possible extension to model feeding precedence relations. Wullink (2005) concludes that an LP based heuristic in combination with scenario selection appears to be the most promising approach. A small selection, selecting two or three scenarios already achieves significant improvements.

The exact algorithm, several proposed heuristics, including the LP based heuristic, and the extension to model feeding precedence relations are explained in Appendix VI.

Reference	Uncertainty	Different precedence relations	Variable time buckets	Developed for a practical application	Usability in a practical application and computational time
Kis (2004)	Not specified	Yes	No	No, mainly theoretical contribution	No, only tested on a small problem instances and compared to Hans (2001).
Wullink (2005)	Yes, by modelling different scenarios	Yes, proposed as model extension based upon the work of Kis, (2004)	No	Yes	Model can become unattractive due to many possible scenarios. However, heuristic is proposed to solve the model.
Masmoudi et al. (2011)	Yes, by using continuous distributions	Not specified	No	Yes	Not specified, since the algorithm is only tested on the specific case. This case consisted out of 18 activities.
Alfieri et al. (2011)	No, only by using a buffer	Yes, extends the work of Kis (2004)	No	Yes	No, not useful for large problem instances. Computational time becomes too large.
Naber and Kolisch (2014)	Not specified	No	No	No, mainly theoretical contribution	No, the proposed model is tested on a problem instance of only 55 activities.
Carvalho et al. (2015)	No, only by using a buffer	Yes	No	Yes, but only useful for the case the article is developed for	Yes, especially designed for a practical application.
Cherkoui et al. (2015)	Yes, by using a reactive approach	No, only finish-to-start	Yes	Yes	No, only tested on a medium problem instance.
Baydoun and Hait (2016)	Not defined	Yes	No	No	No, tested on small problem instances of De Boer (1998)
Naber (2007)	Not defined	No, only finish-to-start	No	No, mainly theoretical contribution	Model is terminated after two hours. Heuristics are suggested to speed up the process.
Cherkaoui et al. (2017)	Yes, by making the schedule more robust by different buffers	Not defined	No	Yes	No. The computational time becomes too large for larger problem instances.

Table 5.5: Verifying requirements with algorithms found

5.5 Conclusion

This chapter provided a step-by-step implementation plan for multi-project planning. We proposed four different steps and explained how these steps can be implemented. These steps are:

- Improve the quality of data
    - Identify the minimum duration per project activity
    - Identify and map precedence relations
    - Define the maximum number of employees working on a project activity
    - Improve the data regarding milestones
    - Define the available regular and non-regular capacity per resource group
    - Make agreements upon the maximum utilization per resource group
- Implement several organizational changes

  We explained the following two organizational changes:
    - Creating awareness and support for multi-project planning
    - An explanation of changing job descriptions

      For example, the tactical planners become responsible for the multi-project view and should stay responsible for the tactical plan during the entire project execution.
- The support of software

  Selection for software support involves the following steps:
    - The make-or-buy decision,
    - Discussing the software requirements
    - Evaluating the feasibility of MS projects.
- Proposing a tactical planning algorithm

  MS Project is not a tactical planning tool. We therefore advise the algorithm of Wullink (2005) that can be used within a planning tool in the future. The algorithm and corresponding heuristics are explained in Appendix VI.

Chapter 6: Conclusion and recommendations

This chapter concludes this thesis. Section 6.1 provides an answer to our central research question. Section 6.2 explains our contributions to both science and practice. Section 6.3 gives recommendations for AWL. Section 6.4 discusses the limitations of this research. Lastly, Section 6.5 proposes future research that can be done as a follow-up on our research.

6.1 Research conclusion

The current planning process at AWL causes too many unmet milestones and requires many ad-hoc changes during the operational planning process. Currently, the number of milestones finished on time is only 49%. This indicates that more than the half of the milestones is not completed on time. This core problem resulted in the research question:

'*How should the planning strategy of AWL be redesigned such that the number of unmet milestones is minimized?*'

We conducted data analysis to determine the effects of unmet milestones. We discovered that the accuracy of the booked and planned hours is low. The accuracy varies between 300% more hours booked than budgeted and 50% more hours budgeted than booked (see Figure 3.6). The average percentage of hired capacity in the last half of 2018 was equal to 27% for the four mentioned resource groups (see Table 3.7). The percentage of working in overtime is equal to 14% in 2018 (see Table 3.8). These numbers confirm that the planning process and the realization thereof is not as desired.

Based upon the analysis of the current situation, we concluded that AWL plans projects individually without considering the effects on other projects. Uncertainties are not incorporated in a project plan. Moreover, project activities are currently not planned in the project plan. The project plan only indicates the lead time for a department. A capacity check is executed afterwards, which results in planning against infinite capacity.

We used the hierarchical planning framework to identify missing planning functions. Furthermore, we analysed the current communication structure. Based upon our observations we conclude that the tactical level is overlooked and poorly addressed by AWL. The missing planning functions mainly concern the tactical level.

To improve the current situation, we redesigned the hierarchical planning framework. We zoomed in on the tactical level and explained what multi-project planning should look like for AWL. We set-up an objective: *"Minimize the variable costs of staff involved during the engineering and assembly process"*, constraints and a corresponding planning horizon of twelve months for multi-project planning. We distinguished between different project activities and the corresponding resource groups that execute these project activities. For example, the project activities mechanical engineering and simulation engineering executed by mechanical engineers and robot simulation engineers respectively. Furthermore, we described the precedence relations between the project activities. We also explained what the output data of multi-project planning should be and what decisions can be made based upon this information. Multi-project planning should result in a production plan with workload distributions per resource group for all incoming and already committed projects.

To make multi-project planning successful and effective, the planning functions should interact with each other and other hierarchical planning levels. In order to do so, we designed a tactical planning meeting. The purpose of this meeting is to gather the required input data for multi-project planning, establish lead times for incoming projects and discuss the possibility to accept more orders based on the current resource utilization. The stakeholders of this meeting are the managing director, a sales representative, a tactical planner, the manager engineering and the manager operations.

The last step to answer the central research question is providing a step-by-step implementation plan. We explained what kind of data should be collected, how awareness and support can be created for the proposed change and how responsibilities of different functions will change. In addition, we gave advice regarding the software that can be used to implement multi-project planning. We provided a possible improvement that can be made with the current used tool; MS Projects. Lastly, we provided an advice regarding a tactical planning algorithm that could be used in the future.

6.2 Contributions to science and practice

This section explains the contributions to science and practice of this research.

6.2.1 Contributions to science

Much attention in research has been paid to detailed production planning and strategic aggregate planning. The tactical planning function is not often addressed in literature. This research is a case study in which we explain how multi-project planning can be deployed in an organization. We provided a practical application of the hierarchical planning framework of Hans et al. (2005). The hierarchical planning levels and planning functions in the framework are tailored for AWL. We distinguished between a tactical *high level* and tactical *low level*, since AWL makes decisions for multiple- and single project respectively. We think that this practical application can be used for educational purposes to compare a real-life case with the existing standard proposed planning framework in literature.

Another contribution to science concerns the integration and interaction of different planning functions and hierarchical planning levels. In literature, almost no attention is given to the integration of different planning functions. In this research, we explicitly emphasized how the interaction and integration between different planning functions should be. We explained the data that should be exchanged and the responsible stakeholders to do this properly. We think that this is a valuable contribution to science because the results can be applicable for other ETO organizations as well.

Finally, we made a state-of-the-art literature overview of tactical planning algorithms developed in the last fifteen years. An important contribution to literature is the mathematical modelling of feeding precedence relations, introduced by Kis (2004). We have seen that the gap between literature and practice is still large when it comes to tactical planning.

6.2.2 Contributions to practice

This report showed the urge to redesign the current planning strategy by showing the number of unmet milestones, the deviation between the budgeted and booked hours and the costs of working in overtime and hiring additional staff.

To improve the current situation, we provided a practical step-by-step implementation plan for multi-project planning in practice. In Chapter 5, we described the steps that are required to implement multi-project planning. These steps are:

- Improve the quality of data
- Create awareness and support for the change
- Change responsibilities of different functions
- Change the software support of multi-project planning

Another practical contribution for AWL is the proposed way of working with MS Projects in Section 5.3.3. We described the possible improvements that can be made with MS Projects. In addition, we explained the steps that are required to do this.

6.3 Recommendations

This section provides recommendations for AWL based upon our research.

Following our report, we recommend AWL to implement multi-project planning as described in Chapter 4. The roadmap for implementing multi-project planning is described in Chapter 5. Implementing multi-project planning will be beneficial for AWL. The main benefit will be less non-regular capacity usage and a more stable workload.

Next to following the roadmap described in Chapter 5, we recommend the following to AWL:

- Operational scheduling process should be reassessed. The current operational scheduling process results in different detailed schedules made in isolation. The multi-project overview is missing at the operational level of control. We therefore recommend AWL to reassess this scheduling process.
- The consequences of the order acceptance method should be visualized and assessed towards the sales employees. In order to make multi-project planning successful the effects of accepting a new project should be visual. Visualizing the effects of accepting as many orders as possible contributes in creating awareness and support for implementing a change.
- AWL should consider another reward structure for the sales employees. The current reward structure result in accepting as many orders as possible, since sales employees receive a bonus above their standard salary (see Section 3.5.1).
- Hiring additional staff should be a decision of tactical planners instead of a decision of operational planners. Capacity flexibility is a characteristic of the tactical planning level.
- Do not focus on an operational utilization of 95% or higher and make new agreements about the operational utilization target. Maximization of the utilization leads to no flexibility against variability in the process. This results in maximization of the waiting times.

6.4 Limitations

This section explains the limitations of this research.

The main limitation of this research is the focus on the assembly and engineering department only. We left the testing and transportation phase out of scope. Including these phases would make the research scope too broad. Furthermore, the transportation phase is left out of scope since project activities are performed at the customer side. However, these two steps require capacity. So, in fact these two steps do influence the availability of staff. Including these phases does not influence the multi-project planning function. However, more project activities should be defined for these project phases as well.

The second limitation of this research is the consideration of just one facility of AWL. Actually, AWL has several facilities that influence the planning process. For example, employees can be allocated to foreign countries, or project activities could be executed by other facilities of AWL. In other words, the supply chain is more complex than proposed in this research.

The last limitation concerns the lists of requirements of software. The list of software requirements for enabling multi-project planning in Section 5.3.2 is not complete. The list is limited to general requirements. Especially the technical requirements need to be refined when AWL is ready to implement a tactical planning tool.

6.5 Suggestions for further research

This section provides several suggestions for further research. We divide this section in suggestions for further research at AWL and suggestions for academical further research.

6.5.1 Suggestions for further research at AWL

We identified missing planning functions in Section 4.1.1. At the strategic level, we saw that there is currently no long-term demand forecasting and aggregate capacity management method present at AWL. We therefore suggest researching the opportunities of developing a long-term forecast at AWL in the future. We think that a forecast of demand has a positive impact on the remaining planning process, since the expected workload is more transparent at an earlier stage. Furthermore, the order intake which is structurally too high will be reduced by having a long-term forecast.

The second suggestion for further research at AWL concerns our advice regarding a tactical planning tool. Our advice is only based on a selection of exact algorithms, since we focused on recent developments in particular (see Section 2.3). Further research could be done regarding the applicability of heuristics for AWL. Heuristics are able the speed up the computational process, which could be beneficial for AWL.

Lastly, the operational scheduling tool, the AWL planner, is only able to allocate resources. It is not a project scheduling tool. We therefore suggest researching the opportunity to improve the operational planning process as well.

6.5.2 Further research in literature

During our research we experienced the diversity of algorithms proposed for tactical planning. However, the number of articles that stress practical implementation of these algorithm is very scarce. We therefore suggest conducting more research in how to practical implement planning algorithms in practice. This research provided a practical application of multi-project planning, but did not implement a tactical planning tool. We do think that implementing mathematical models can provide great benefits for AWL and organizations in general.

Interaction and integration of different departments and hierarchical planning levels is an important aspects of this research. During our literature review, we mentioned that most articles emphasized the mathematical aspects and barely considered interaction of integration with other planning levels and functions. However, without proper integration and interaction, the algorithm will be less successful. We therefore suggest doing more research on how to integrate different planning levels and how they should interact between each other.

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Appendix I: Example of a project plan

This appendix shows a project plan for a single project made in MS projects. This project plan is based on throughput times. The planners do not plan project activities in the project plan, but only indicate when a department has to execute activities. Furthermore, we see that precedence relations are currently not modelled. Furthermore, there is no buffer visual in the project plan.

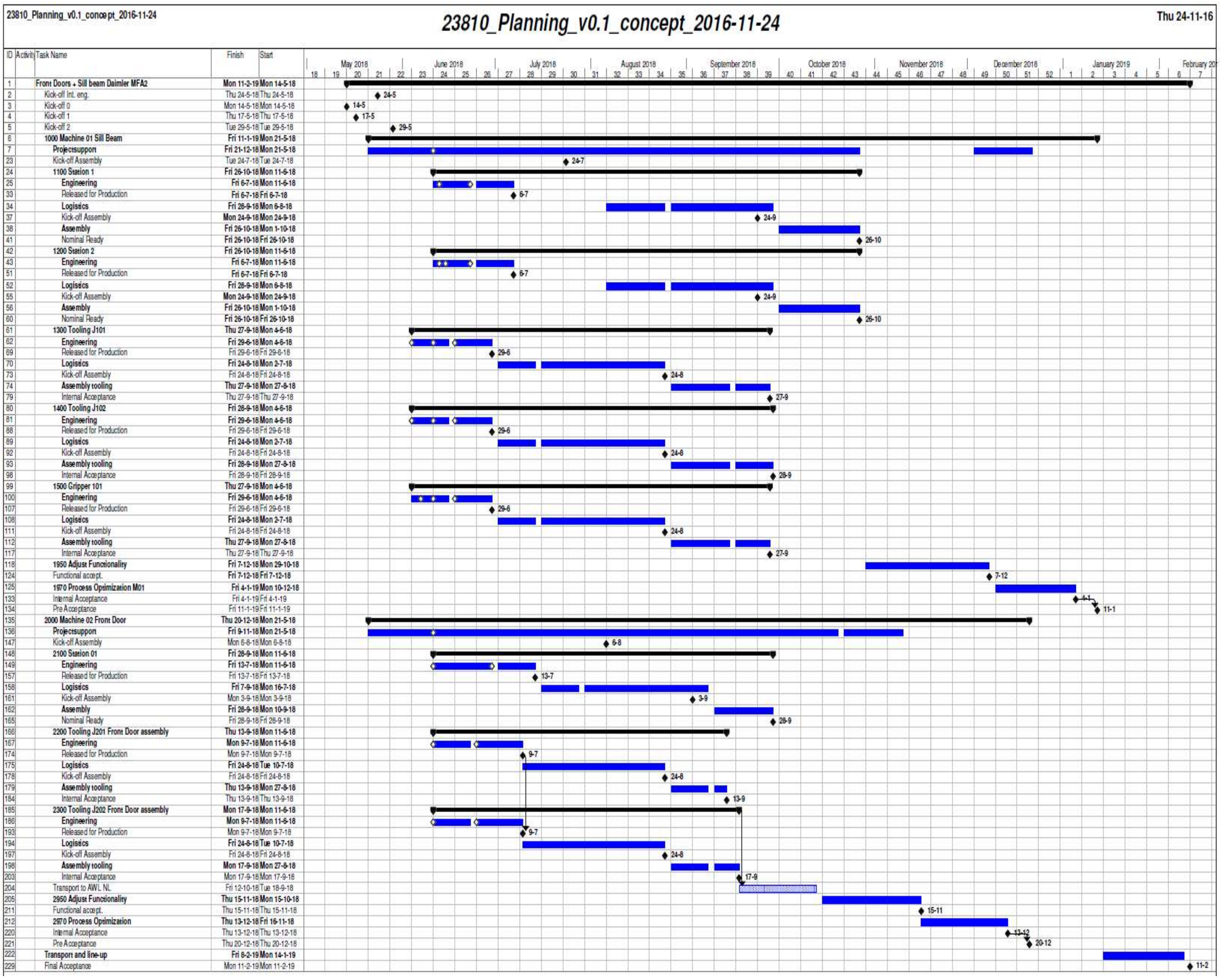

Figure I.1: Example of a project plan made in MS Projects

Appendix II: Example of multi-project planning

This appendix explains the importance of multi-project planning. The example is an adjusted version of the example of Meijerink (2003).

Practical example

We plan two projects that both consist of four identical activities. Each activity has a minimum duration and requires capacity of a specific resource group. The required capacity column indicates the number of FTEs that are required to complete the activity.

First we consider project 1. The input data for project one is given in Table II.1.

Activities	**Minimum duration (days)**	**Release date (days)**	**Due date (days)**	**Required capacity (FTE)**	**Required resources**
Engineering (1)	50	0	70	6	Engineers
Nominal assembly (2)	20	0	100	3	Mechatronic technicians
Nominal commissioning (3)	10	50	110	3	Programmers
Functional assembly (4)	20	70	130	3	Programmers

Table II.1: Input data project 1

Figure II.1 visualizes the sequence in which the activities should be executed with the corresponding precedence relations.

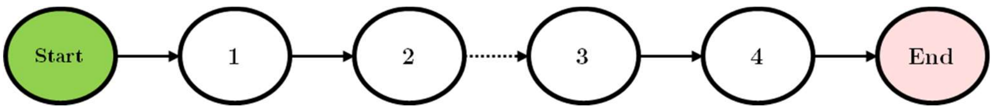

Figure II.1: Precedence relations for both projects

The dashed line indicates a feeding precedence relation between activity 2 and 3. If 50% of activity 2 is completed, activity 3 may start. The other precedence relations are finish-to-start relations, so the succeeding activity can only start if the predecessor activity is completely finished.

Single project planning – infinite capacity

The example starts by making a single project plan for project one without taking capacity relations into consideration.

The result is a single project plan based upon throughput times. Figure II.2 shows the plan of activities based on throughput times.

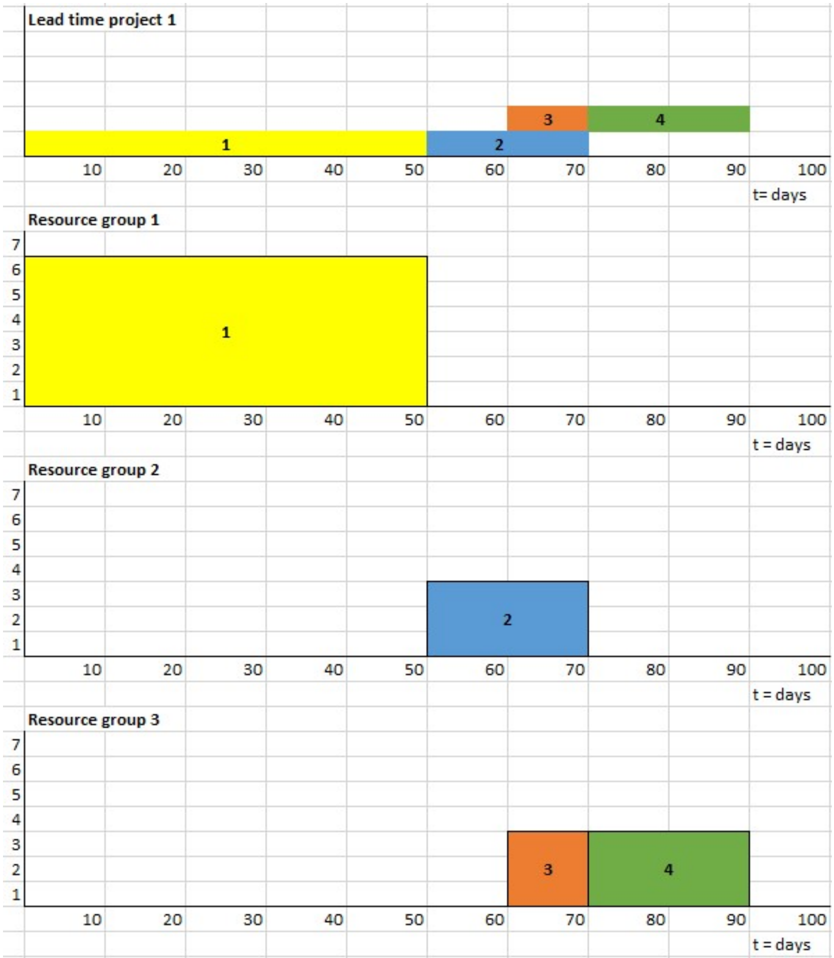

Figure II.2: Single project plan – infinite capacity

Single project planning – finite capacity

Now, we assume that available capacity is limited. Planning a single project while keeping capacity restrictions into consideration results in single project plan against finite capacity. Planning with finite capacity implies that the planner decides to either plan longer lead-times or use non-regular capacity, if there is a capacity shortage. The result is a plan based upon workload-dependent lead times.

We assume that we have 4 available engineers, 3 mechatronic technicians and 2 programmers available for project 1.

The planner has to decide between two options: the planner hires additional staff, such that the project is finished on time, or the planner plans longer lead times without hiring additional staff. Both options are provided in Figure II.3 and Figure II.4 respectively.

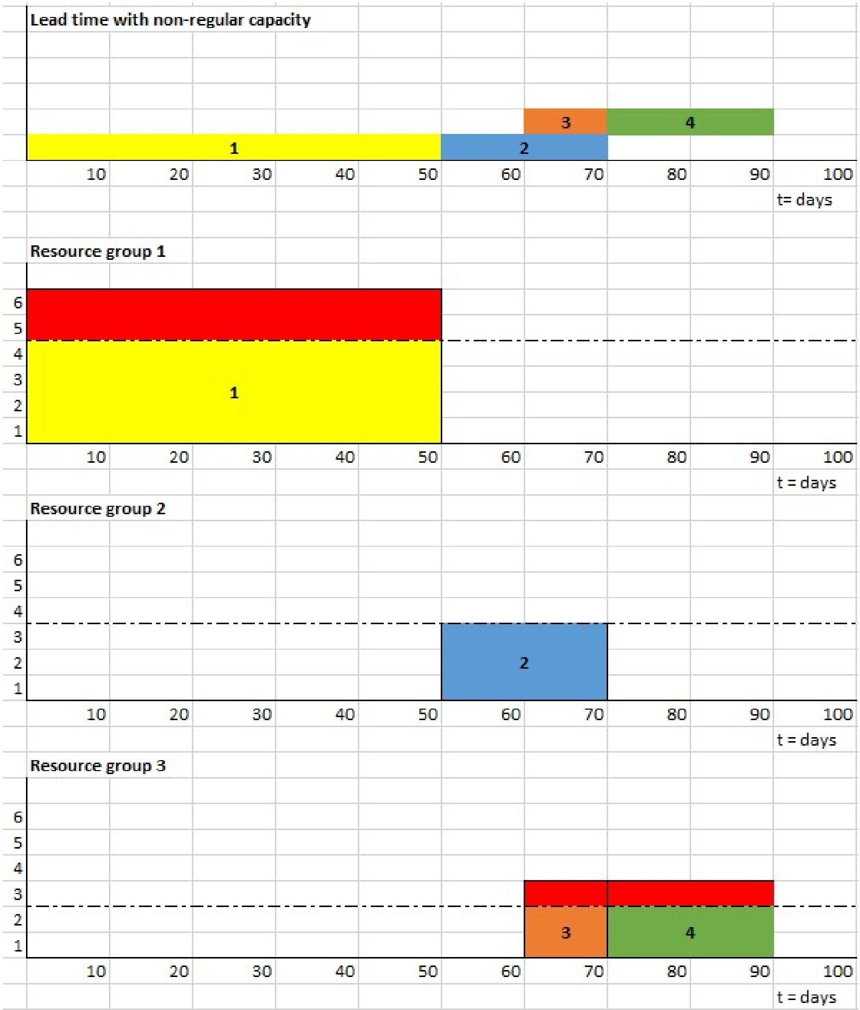

Figure II.3: Single project plan – hiring additional staff

Or we can extend our lead time. By doing so, we do not need to hire additional staff.

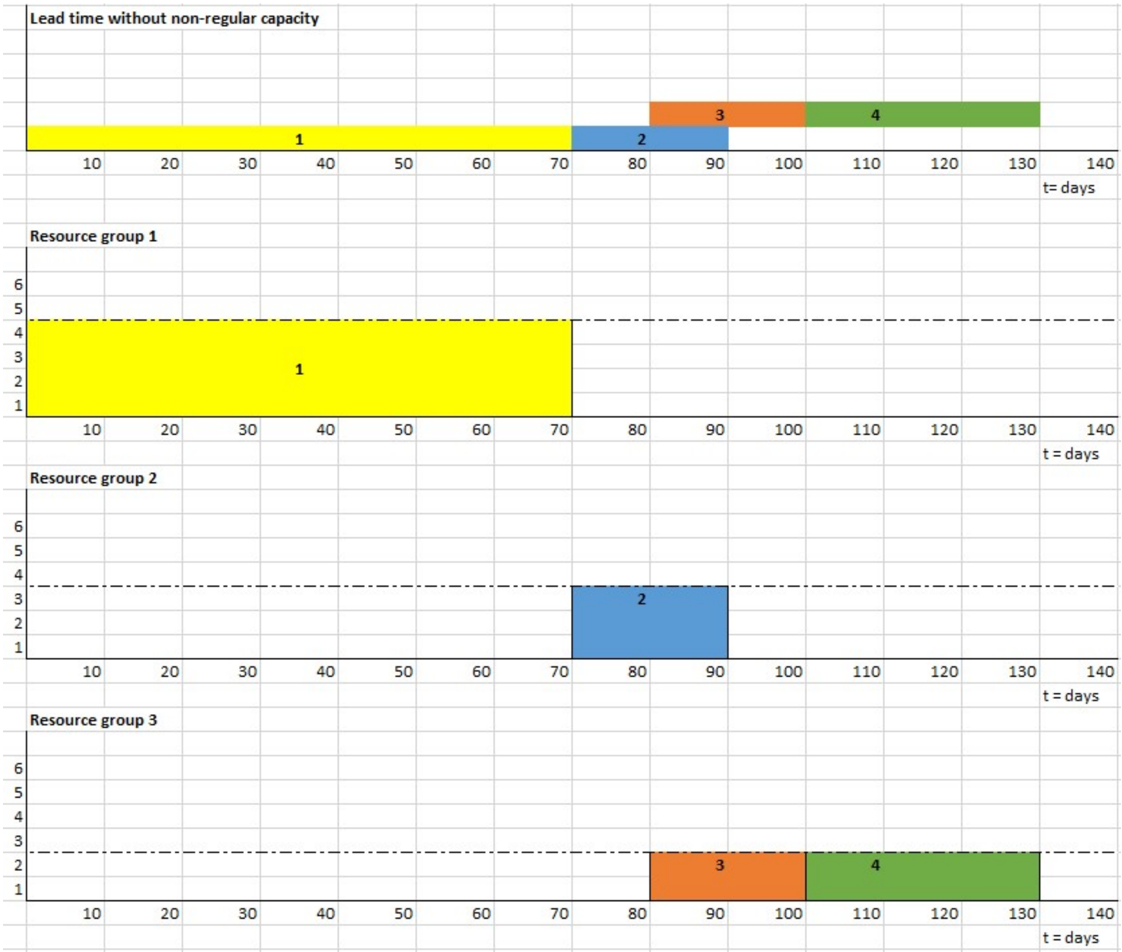

Figure II.4: Single project plan – extending lead times

Multi-project planning – infinite capacity

In practice, multiple projects are executed simultaneously. To illustrate this, we plan two projects simultaneously and visualize the effects. Details of project 2 are illustrated in Table II.2.

Activities	**Minimum duration (days)**	**Release date (days)**	**Due date (days)**	**Required capacity (FTE)**	**Required resources**
Engineering (1)	30	0	40	3	Engineers
Nominal assembly (2)	20	0	60	2	Mechatronic technicians
Nominal commissioning (3)	10	30	80	2	Programmers
Functional assembly (4)	20	40	100	2	Programmers

Table II.2: Input data project 2

The lead time of both projects are visualized in Figure II.5.

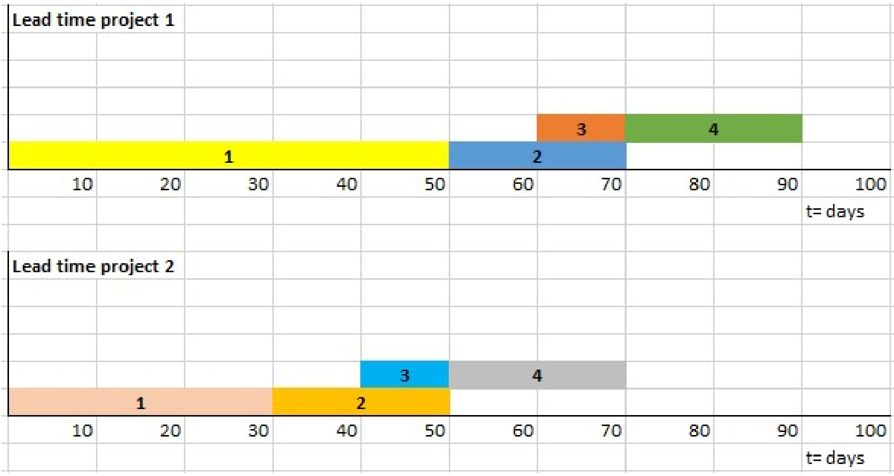

Figure II.5: Multi-project plan – lead times

The effect on three resource groups is visualized in Figure II.6.

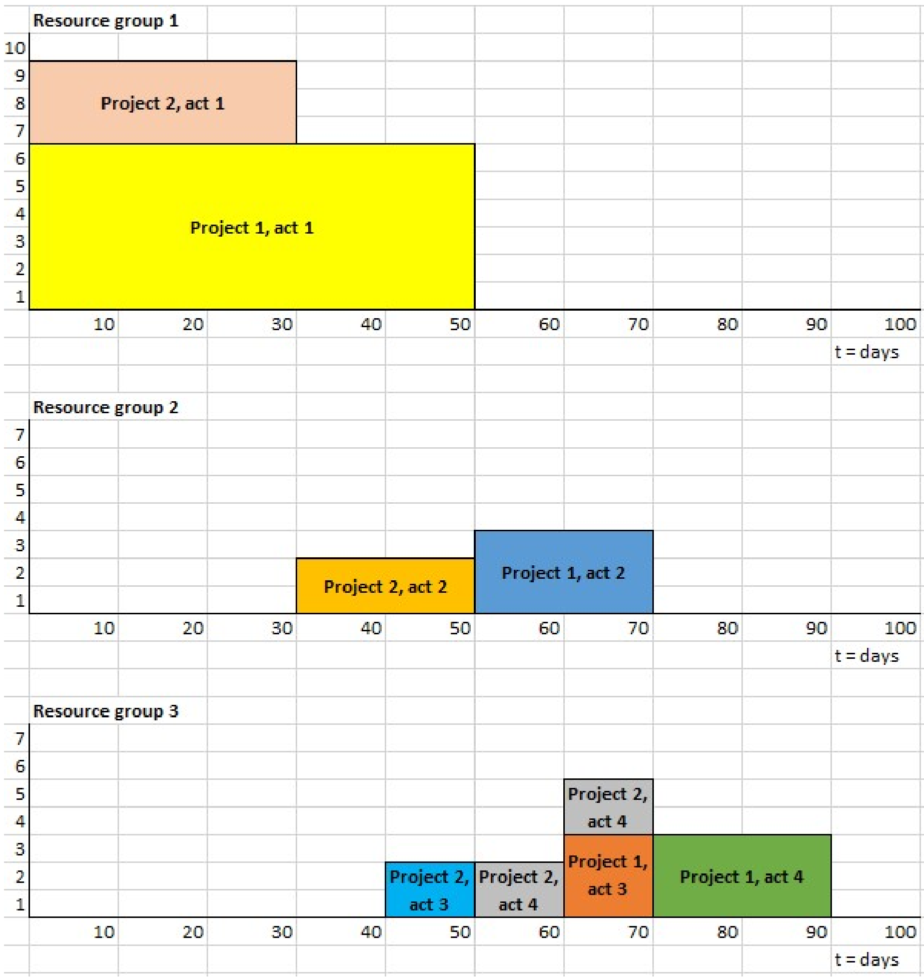

Figure II.6: Multi-project planning – resource requirements

Multi-project planning – finite capacity

In reality, multiple projects are executed simultaneously while there is finite capacity available. For planning two projects simultaneously, the following resources are available: 8 engineers, 2 mechatronic technicians and 2 programmers.

The planner makes a plan based upon the available capacity. The plan for both projects looks as follows:

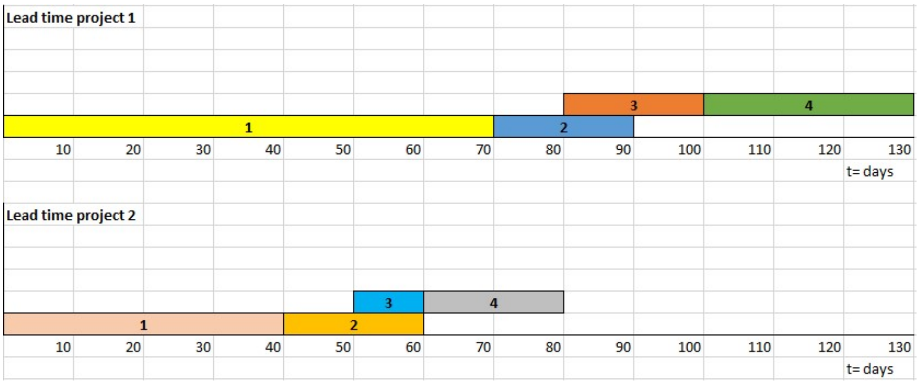

Figure: II.7: Plan based upon available capacity

We see that the planner decided to extend the due dates for both projects. However, the deadlines are still reached. There was no non-regular capacity needed to complete this plan. Figure II.8 shows the resource request for this plan:

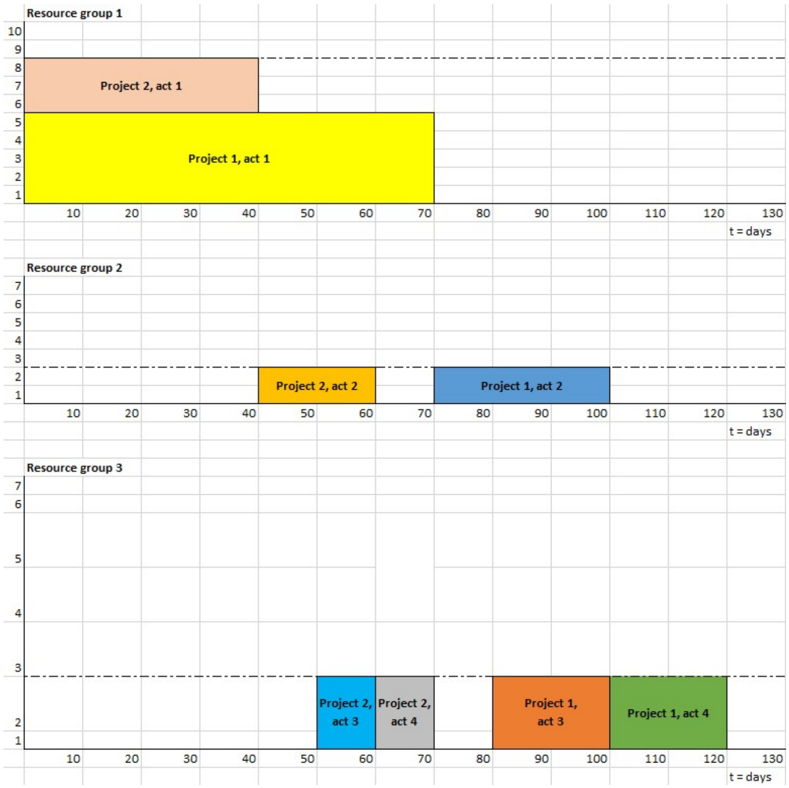

Figure II.8: Resource request for plan based upon available capacity

Appendix III: Tables for redesign planning framework

This appendix provides the information for the redesign of the planning framework. The appendix consists of two tables. The content of the table is set up with the aid of experts of AWL. The 'as is' situation of the planning framework is based upon Table III.1. Table III.2 presents the information for the redesign of the hierarchical planning framework.

Hierarchical level of control	**Scope**	**Based on estimation of actual demand**	**Capacity flexibility**	**Horizon of level of control**	**Decision maker**	**Decision(s)**	**Horizon of decision(s)**	**KPIs**	**Uncertainties**
Strategic	Global and local; *all facilities*	Based on estimation and targets	Structural flexibility, hiring staff for a longer period: 1 year	2 years	Board of directors	Order intake of all facilities	2 years	Order intake YTD EBITDA Solvability	Occurrence of demand
Tactical	Local; *AWL NL*	Based on actual demand	No decisions made upon capacity extensions	9 months	Tactical planners	Lead-time and milestones per project	9 months	% of milestones completed in time	Staff availability, capacity request
					Cost engineers	Budget calculation	9 months	Accuracy of budget calculation	Work content
					Sales department	Acceptance of an order	9 months	Order intake amount YTD	Order acceptance, Timing of an order, rush order

Operational *Offline*	Local; *AWL NL*	Based on actual demand	Incidental staff hiring for a short period, 1-6 weeks in advance	2 – 8 weeks	Managing Director	Priority decisions of an order	9 months	Realized order intake	Order acceptance
						Decisions regarding rush order	Daily – 1 week	Operational utilization	Timing of an order
					Manager Operations	Out of control issues of projects	Daily – 6 months	% of milestones completed on time	Capacity request, Staff availability, Material availability
					Manager engineering	Engineering issues	Daily – two months	% of milestones completed on time	Staff availability
					Manager logistics	Procurement of long-lead time items	10 weeks – 20 weeks	Material availability	Material availability
						Procurement of BOM material	6 weeks		
					Engineers	Work content of the project	Daily – 2 months	% of milestones completed on time	Work content, staff availability, Engineering details are not fixed
					Team leaders	Timing of activities of several projects, out of control issues of projects	Daily – 2 weeks	% of milestones completed on time	Staff availability Uncertain processing times Material availability

					Project coordinators	Project scheduling	Daily – 2 weeks	% of milestones completed in time	Staff availability Uncertain processing times Material availability
					Operational planners	Staff allocation	Daily – 2 weeks	Number of dummy hours	Staff availability
Operational *Online*	Local; *AWL NL*	Based on actual demand	None	Daily	Project coordinators	Ad-hoc project issues	Daily	% of milestones completed in time	Material availability,
					Operational planners	Ad-hoc project issues	Daily	Number of changes in project schedule	Mistakes made earlier in the process

Table III.1: Rationale content hierarchical framework - observed situation

The redesign of the planning framework is based upon Table III.2.

Hierarchical level of control	**Scope of decisions**	**Demand or forecast based**	**Capacity flexibility**	**Horizon of level of control**	**Decision makers**	**Decision(s)**	**Horizon of decision**	**KPIs**	**Uncertainties**
Strategic	Global organization – *All facilities*	Based on forecasts	Structural flexibility, hiring staff for a longer period of time; 1 year	2 years	Board of directors	Order intake of all facilities	2 years	Order intake YTD EBITDA Solvability	Occurrence of demand
Tactical *High level*	Local organization – *AWL NL and per segment*	Based on forecasts and actual demand	Temporal: hiring staff for several months	1 year	Managing Director	Order intake facility NL Decisions regarding rush orders	9 months – 1 year	Order intake per facility YTD EBITDA Solvability	Occurrence of demand Timing of an order
					Manager operations	Temporal staff expansion operations – *for all projects*	Until 1 year	% of projects delivered in time Utilization per resource group *Operations*	Staff availability
					Manager Engineering	Temporal staff expansions engineering – *for all projects*	Until 1 year	Engineering quality Utilization per resource groups *Engineering*	Staff availability
					Manager Logistics	Price agreements Quantities Delivery times with suppliers	Until 1 year	Quality of delivered materials % Materials delivered in time	Material delivery: *long lead time items*

					Sales Manager	Order acceptance	Until 1 year	Order intake per segment	Project content, timing of an order, staff availability, capacity request
					Tactical planner	Multi-project planning: external workload dependent lead times	9 months - 1 year	Amount of non-regular capacity used	All mentioned uncertainties above
Tactical *Low level*	Local organization – *per project*	Based on actual demand	Temporal flexibility, hiring employee for several months or weeks	9 months	Managing Director	Project issues with strategic importance	9 months	Operational utilization	Rush order
					Manager operations	Hiring temporarily capacity for one project	9 months	Percentage of milestones completed in time	Availability staff
					Manager Engineering	Hiring temporarily capacity for one project	9 months	Percentage of milestones completed in time	Availability staff
					Manager Logistics	-	-	Material availability on time	Material delivery by external companies
					Account manager	Negotiation	9 months	Succeeding percentage during negotiation phase	Competitiveness of AWL compared to competitors

					Tactical planners	Single project planning – start and internal due dates for engineering and assembly department	9 months	Percentage of milestones completed in time	All mentioned uncertainties above
					Engineers	Concept engineering / macro process planning	9 months	Customer requirements change often over time	Work content of the project Precedence relations of a project
					Cost engineer	Cost calculation of project	9 months	Accuracy of cost calculation	Work content of the project
					Logistic engineer	Procurement of long lead time items	9 months	On-time material availability (%)	Material delivery
Operational *Offline*	Local organization – *per sub-assembly of a project*	Based on actual demand	Incidental flexibility	2 - 8 weeks	Manager operations	Out of control issues of projects	Daily – two weeks	% of milestones completed in time	Staff and material availability
					Manager engineering	Out of control engineering issues	Daily – two weeks	% of milestones completed in time	Staff and material availability
					Engineers	Detail engineering (micro process planning)	2 weeks	Exact project content for detail engineering	Mistakes made in the engineering process

					Logistic engineer Team leaders assembly Operational planner	Ordering of BOM materials Timing of a sub-assembly Out of control issues of projects Project schedule and staff allocation	6 weeks 2 weeks 2 weeks	On-time material availability (%) % of milestones completed in time Dummy hours	Material availability per project Material availability per project Staff availability
Operational *Online*	Local organization – *per job of a project*	Based on actual demand	None	Daily	Operational planners	Ad-hoc planning issues	Daily	Number of changes in the project schedule	Material availability per job

Table III.2: Rationale redesign content hierarchical framework

Appendix IV: Information for design tactical planning meeting

This appendix provides the information that should be exchanged during the tactical planning meeting. We distinguish between input, output, decisions and actions after the meeting per stakeholder. The content of this table is set up together with experts of AWL.

Stakeholder	**Input**	**Output**	**Decision**	**Action after meeting**
Managing director	Target: order intake AWL per segment	Current order intake per segment (YTD) Current utilization of engineering and assembly department	Strategic importance of (rush) orders Structural capacity extensions of engineering and assembly department	Provide update of output and decisions to board of directors
Tactical planner	Multi-project overview and their status: Possible internal and external due dates Estimation of milestones	-	-	Update the multi-project view based upon actual order intake and staff utilization. Discuss internal and external due dates with sales manager regarding a single project
Sales manager	Forecast incoming orders for entire planning horizon per segment Concrete opportunities with project content	Possibilities for accepting or rejecting new incoming orders	Order acceptance	Provide information to account managers for possibility order acceptance of new incoming orders
Manager operations	Update staff utilization: assemble resource groups	Requirements for assembly department based on forecast of possible incoming orders	Temporal capacity extensions	Update team leaders and operational planner regarding incoming projects during operational meeting
Manager engineering	Update staff utilization: engineering resource groups	Requirements for engineering department based on forecast of possible incoming orders	Temporal capacity extensions	Update team leaders and operational planner about incoming projects during operational meeting

Table IV.1: Rationale behind information flow during the tactical planning meeting

Appendix V: KPI formulas

This appendix provides formulas to illustrate how the KPIs described in Section 5.2.4 should be measured. The KPIs that we explain are:

- Customer satisfaction
- Percentage of projects delivered on time
- Percentage of milestones completed on time
- Percentage of hired capacity
- Percentage of working in overtime of AWL employees
- The deviation between booked and budgeted hours
- The number of revisions of a project plan
- The number of daily ad-hoc issues at the operational level

Customer satisfaction

Customer satisfaction is a measurement that is hard to quantify, because it is a subjective concept. There are several factors that influence customer satisfaction. In order to investigate the customer satisfaction, AWL wants to set up a questionnaire to retrieve information of the customer. Together with the managing director we investigate the following aspects that should be included in the questionnaire:

- Quality of the machine
    - The quality of the performance of the machine depends upon the cycle time of welding one part. The cycle time should be as described in the specifications of the machine.
    - The defect rate determines the quality of the machine as well. The defect rate could be calculated as the ratio between 'OK' and 'NOT OK' produced parts.
- On-time delivery performance
    - The on-time delivery performance can be measured by KPI 2. In the questionnaire it could be verified whether the customer is satisfied by the delivery performance of AWL.
- Budget exceeding per project
    - The difference between the original budget of the project and the final costs of the delivered machine can be used as an indicator of the customer satisfaction.

Percentage of projects delivered on time towards customer side

This KPI measures the delivery performance of AWL per project towards the customer side. This KPIs does not measure the final customer acceptance, but the timing of the transportation towards the customer side. We have observed that this is a critical step in the delivery process. This KPI could be measured by the number of final acceptance tests completed on time:

$$KPI\ 2 = \left(1 - \left(\frac{Final\ acceptance\ tests\ finished\ on\ time}{Total\ number\ of\ projects}\right)\right) * 100\%$$

Percentage of milestones completed on time

This KPI can be measured by the number of milestones that are completed on time. An indicator function should be used to measure the number of milestones completed on time. In total there are X milestones: $m_{1,\ldots,}, m_x$. Every milestone m has a deadline d_m and an actual finish date f_m. If the actual finish date is smaller or equal to the deadline of the milestone, the indicator function is equal to 1 and 0 otherwise. To calculate the percentage of milestones completed on time, we divide the number of milestones completed on time by the total number of milestones.

$$KPI\ 3 = \frac{\sum_{m=1}^{X} I_{d_m} \leq f_m}{Total\ number\ of\ milestones} * 100\%$$

Percentage of hired capacity

This KPI should be measured and monitored for all resource groups. The KPI shows the ratio between hired employees and AWL employees. We recommend to measure the KPI with the following formula:

$$KPI\ 4 = \frac{Number\ of\ hired\ employees}{Number\ of\ AWL\ employees + number\ of\ hired\ employees} * 100\%$$

Percentage of working in overtime

This KPI should be measured and monitored for all resource groups for AWL employees. We recommend to measure this KPI in the following way:

$$KPI\ 5 = \frac{Number\ of\ booked\ hours\ in\ overtime}{Total\ booked\ hours} * 100\%$$

Deviation between booked and budgeted hours per project

This KPI measures the deviation between the estimated required hours for a project and the realization thereof. The deviation influences the planning accuracy. We recommend to measure this KPI in the following way:

$$KPI\ 6 = \frac{Booked\ hours\ per\ project}{Budgeted\ hours\ per\ project} * 100\%$$

Number of revisions of a project plan

This KPI can be measured by the number of milestones that are not finished as planned per project. Delay in a project requires a revision of the project plan. An indicator function should be used to measure this KPI. There are P milestones per project: $m_1, \ldots, m_p$. Every milestone m has a deadline d_m and an actual finish date f_m. If the actual finish date is smaller or equal to the deadline of the milestone, the indicator function is equal to 1 and 0 otherwise. We therefore recommend to measure this KPI in the following way:

$$KPI\ 7 = \sum_{m=1}^{P} I_{d_m} \leq f_m$$

Number of ad-hoc issues at the operational level

This KPI can be measured as the summation of daily changes in the operational plan. Ad-hoc changes that cause disruptions in the operational planning process mainly concern changing staff allocations. We therefore recommend to measure the number of changing staff allocations. The AWL planner is able to track the number of changing staff allocations. (no formula needed)

Appendix VI: Tactical capacity planning algorithm

In this appendix we explain a tactical capacity planning algorithm that is especially useful for ETO organizations that face uncertainty. We propose a Mixed Integer Linear Programming (MILP) model and several heuristics. The MILP model minimizes the expected costs for non-regular capacity over different scenarios. The capacity flexibility options are, outsourcing, hiring and working in overtime. The following concepts have to be introduced in order to understand the algorithm.

Order plan and loading schedule

Order plan π for order j specifies the time period in which job (b, j) is allowed to be processed, restricted by precedence relations. The model generates a loading schedule for each order j. The loading schedule specifies how jobs (b, j) are executed. The loading schedule specifies the fraction Y_{bjt} of job (b, j) that will be performed in period t.

Scenarios and modes

We assume that the planner identifies uncertain activities. Per uncertain activity, a limited number of work contents may occur, which we call *modes*. A *scenario* is a case where each uncertain activity occurs in a specific mode. The central idea of this algorithm is that uncertain activities will be planned in time periods with the largest amount of excess capacity. By doing so, the amount of non-regular capacity will be minimized.

The model proposed by Wullink (2005) is a generalization of the model proposed by Hans (2001). For a detailed explanation of this model we refer to Hans (2001).

Scenario based model

Indices

t	period $(t = 0, \dots, T)$
σ	scenarios $(\sigma = 1, \dots, l)$
j	order $(j = 1, \dots, n)$
(b, j)	b-th job of order j $(b = 1, \dots, n_j)$
i	resources $(i = 1, \dots, K)$

Scenario dependent parameters

p_{bj}^{σ}	work content of activity (b, j) in scenario σ
p_{bj}^{m}	work content of activity (b, j) in mode m
q^{σ}	probability of scenario σ
q_{bj}^{m}	probability that activity (b, j) occurs in mode m
z_{bj}^{σ}	the mode in which activity (b, j) occurs in scenario σ
v_{bji}^{σ}	the fraction of activity (b, j) that is performed on resource group in scenario σ
mc_{it}^{σ}	total regular capacity of resource group i in period t in scenario σ
s_{it}^{σ}	maximum allowed outsourced capacity on resource group i in period t in scenario σ

h_{it}^{σ} maximum allowed hired capacity on resource group i in period t in scenario σ

o_{it}^{σ} maximum overtime capacity on resource group i in period t in scenario σ

<u>Scenario independent parameters</u>

μ_j number of uncertain jobs of order j

$\Pi(\Pi_j)$ set of all feasible order plans for order j

a_j^{π} π-th order plan for order j

ς_s subcontracting cost per time unit

ς_h hiring cost per time unit

ς_o overtime cost per time unit

r_j release date for order j

$\bar{d}_j$ deadline for order j

ω_{bj} minimum duration of job (b, j)

<u>Decision variables</u>

S_{it}^{σ} outsourced production hours for resource group i in period t in scenario σ

H_{it}^{σ} hired production hours for resource group i in period t in scenario σ

O_{it}^{σ} overtime production hours for resource group i in period t in scenario σ

X_j^{π} binary variable that is 1 when order plan a_j^{π} is selected for order j

Y_{bjt} fraction of job (b, j) executed in period t

<u>Model</u>

$$z_{ILP}^{*} = \min \sum_{\sigma=1}^{l} q^{\sigma} \left(\sum_{t=o}^{T} \sum_{i=1}^{K} \varsigma_s S_{it}^{\sigma} + \varsigma_h H_{it}^{\sigma} + \varsigma_o O_{it}^{\sigma} \right) \quad (1)$$

Subject to:

$$\sum_{\pi \epsilon \Pi_j} X_j^{\pi} = 1 \ (\forall \mathrm{j}) \quad (2)$$

$$Y_{bjt} \leqq \frac{\sum_{\pi \epsilon \Pi_j} a_{bjt}^{\pi} \, x_j^{\pi}}{\omega_{bj}} (\forall \mathrm{b,j,t}) \quad (3)$$

$$\sum_{t=r_j}^{T} Y_{bjt} = 1 \ (\forall \mathrm{b,j}) \quad (4)$$

$$\sum_{j=1}^{n} \sum_{b=1}^{n_j} p_{bj}^{\sigma} v_{bji}^{\sigma} Y_{bjt} \leqq mc_{it}^{\sigma} + S_{it}^{\sigma} + H_{it}^{\sigma} + O_{it}^{\sigma} \ (\forall \mathrm{i,j,t}) \quad (5)$$

$$\sum_{i=1}^{K} S_{it}^{\sigma} \leqq s_t^{\sigma} (\forall \mathrm{t}, \sigma) \quad (6)$$

$$\sum_{i=1}^{K} H_{it}^{\sigma} \leqq h_t^{\sigma} (\forall \mathrm{t}, \sigma) \quad (7)$$

$$\sum_{i=1}^{K} O_{it}^{\sigma} \leqq o_t^{\sigma} (\forall \mathrm{t}, \sigma) \quad (8)$$

$$X_j^{\pi} \epsilon \{0,1\} \ (\forall \mathrm{j}, \pi \in \Pi_j \subset \Pi) \quad (9)$$

$$All\ variables \ \geq 0 \quad (10)$$

The objective (1) minimizes the costs of subcontracting, hiring and overtime over all resource groups i and periods t over all scenarios σ. Constraint (2) and (9) ensure that one order plan is selected for each order j.

To model precedence relations between jobs, we use column generation. Activity (b,j) is allowed to be executed in time period t, if and only if element a_{bjt}^{π} in column π is 1. Since only feasible order plans are considered, binary variable X_j^{π} is used.

Relations (3) ensures that the minimum duration of a job is respected. Constraint (4) makes sure that all work is done. Constraint (5) until constraint (8) are capacity relations. The relations make sure that all work that is not completed yet, is completed with the aid of non-regular capacity. Furthermore, all variables have to be larger or equal to zero.

Model extension for precedence relations

Wullink (2005) also proposes the opportunity to model feeding precedence relations. This is based upon the work of Kis (2004). Kis uses a binary decision variable Z_{bjt} that indicates whether activity (b,j) is allowed to be performed in periods $t \in \{r_{bj}, \dots, d_{bj} - \omega_{bj}\}$ that overlap with predecessor of activity (b,j).

These precedence relations are formulated as follows:

$$Y_{bjt} \leqq \frac{Z_{bjt}-Z_{kjt}}{\omega_{bj}} \left(\forall (\mathrm{k},\mathrm{j}) \in \Omega_{bj}, t \in \left\{r_{kj}, \dots, d_{bj} - \omega_{bj}\right\}\right) \tag{9}$$

$$Y_{bjt} \leqq \frac{Z_{bjt}}{\omega_{bj}} \left(\forall (\mathrm{b},\mathrm{j},\mathrm{t}) \in \left\{r_{bj}, \dots, \min\left\{r_{kj} - 1, d_{bj} - \omega_{bj}\right\}\right\}\right) \tag{10}$$

$$Y_{bjt} \leqq \frac{1-Z_{kjt}}{\omega_{bj}} \left(\forall (\mathrm{k},\mathrm{j}) \in \Omega_{bj}, t \in \left\{max\left\{d_{bj} - \omega_{bj} + 1, r_k\right\}, \dots, \min\left\{d_{kj} - \omega_{kj,}, d_{bj}\right\}\right\}\right) \tag{11}$$

$$Z_{bjt} \leqq Z_{bj,t+1} (\forall \mathrm{b},\mathrm{j},\mathrm{t} \in \left\{r_{bj}, \dots, d_{bj} - \omega_{bj} - 1\right\}) \tag{12}$$

Constraint (9) ensures that the fraction (b,j) executed in time window: $t \in \left\{r_{kj}, \dots, d_{bj} - \omega_{bj}\right\}$ must be smaller than $\frac{1}{\omega_{bj}}$ if successor activities $(\mathrm{k},\mathrm{j}) \in \Omega_{bj}$ are not started yet, and 0 otherwise.

Constraint (10) ensures that the fraction of activity (b,j) is smaller than $\frac{1}{\omega_{bj}}$, if (b,j) is allowed to be executed in time window: $t \in \left\{r_{bj}, \dots, \min\left\{r_{kj} - 1, d_{bj} - \omega_{bj}\right\}\right.$.

Constraint (11) ensures that, on the domain $t \in max\left\{d_{bj} - \omega_{bj} + 1, r_k\right\}, \dots, \min\left\{d_{kj} - \omega_{kj,}, d_{bj}\right\}$, the fraction of activity (b,j) can only be larger than 0 if an activity $(\mathrm{k},\mathrm{j}) \in \Omega_{bj}$is not executed.

Constraint (12) ensures that integer variable Z_{bjt} must always be smaller or equal to Z_{kjt} in the next period.

Heuristics proposed by Wullink (2005)

The MILP model proposed by Wullink (2005) is an exact model. The problem is complex, due to the large number of possible scenarios. The deterministic resource loading problem is proven to be *NP-hard in the strong sense* by Kis (2004). Incorporating uncertainty increases the complexity of the model. The computational time of the model may become too large. Wullink (2005) therefore mentions several options for approaching the solution by using heuristics. We divide heuristics in two categories: 1. Constructive heuristics and 2. Improvement heuristics.

Constructive heuristics

Constructive heuristics start without an initial solution and construct a feasible solution from scratch. Examples of constructive heuristics are Incremental Capacity Planning Algorithm (ICPA), a LP-based heuristic, proposed by De Boer (1998) and the Largest Activity Part (LAP) proposed by Wullink (2005).

Incremental Capacity Planning Algorithm

The ICPA heuristic starts with sorting jobs, based upon due dates or slack. Thereafter ICPA plans jobs in at most two phases. In the first phase, the algorithm plans as much and as early as possible with the smallest deadline (or least slack) without using non-regular capacity. The second phase starts if the job is not completely finished. If otherwise, the algorithm continues planning the second job. The second phase allows using non-regular capacity such that the job is completed before the deadline.

LP-based heuristic

Precedence constraints cannot be modelled in a LP model. This LP-heuristic relaxes the precedence constraints and repairs the violated constraints iteratively. The heuristic narrows the time window if precedence constraints are violated. If a precedence constraint is violated the start date of job j is smaller than the due date of job i (if job $i \rightarrow j$). One possible way to repair a violated precedence constraint is by using a ratio of non-regular capacity in the specific time window. New release and due dates are determined and the LP-problem is solved again. The procedure is repeated until no precedence relations are violated anymore.

Largest Activity Part (LAP)

LAP is a constructive heuristic that plans activities in four phases. In phase one, LAP plans all ‘trivial’ activities. Trivial activities have a minimum duration equal to the size of the time window. In phase two, LAP plans activities that only use regular capacity. In phase three, LAP also uses non-regular capacity to plan activities and in phase four, the remaining work content is planned in non-regular capacity.

Advantages of constructive heuristics:

- Simple heuristics that improve multi-project planning
- Computation time for constructing a plan is shorter

Disadvantages of constructive heuristics:

- Do not guarantee an optimal solution
- LP-solver is required for an LP-heuristic
- Assumes infinite non-regular capacity, which is an unrealistic assumption

Improvement heuristics

Improvement heuristics may start with either a feasible or infeasible solution. Wullink (2005) proposes three types of improvement heuristics. First he proposes a heuristic that use a constructive heuristic to generate a feasible solution. Thereafter he suggests a heuristic that ignores precedence constraints, repairs the violated precedence constraints iteratively and generates a feasible solution. Finally, he suggest a local search heuristic that starts with an infeasible solution.

Type 1: Van Krieken LP based heuristic

Van Krieken (2001) proposes to use adaptive search in combination with linear programming and uses a regret factor to select an activity. The selected activity is then planned like the ICPA. If all activities are planned, the algorithm stops. For a more detailed description, we refer to Van Krieken (2001).

Type 2: Gademann and Schutten (2005)

Gademann and Schutten (2005) suggest H_{enum}; an approach to repair an infeasible order plan. In every iteration a pair of violated precedence constraints is repaired. The violated precedence constraints with the least slack are repaired first. Slack is defined by the due date of the last activity and the start date of the first activity minus the processing times of both jobs. This procedure is repeated until there are no more violated precedence relations.

Type 3: Shadow price heuristic (SPH)

SPH needs a feasible solution to start with. In every iteration, the heuristic retrieves shadow prices. Shadow prices are used to estimate the expected improvement of all possible changes in the time window of every activity. The heuristic starts with the highest yield. The heuristic then re-optimizes the base model to obtain a new solution and new shadow prices. The heuristic stops if no further improvements are found.

Advantages improvement heuristics:

- Outperforms constructive heuristics

Disadvantage improvement heuristics:

- More complex than constructive heuristics
- LP-solver required for LP based improvement heuristic

We refer to Wullink (2005) for a more detailed description of these heuristics.