Insights into the importance of scientific methods for tactical multi-project planning at AWL

by Jeroen Evers

November 2013

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Master Thesis Industrial Engineering & Management
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Preface

Before you lies the research report for me to complete the master program Industrial Engineering Management at University of Twente. I have started my research period at AWL in May 2013. Through the conduction of interviews with people from various departments and several positions, I was able to learn about the company quickly. After only a few days, I felt right at home at AWL. Therefore, I thank everyone at AWL for their hospitality, time, and help.

Originally, the goal of my project was to discover why intermediary project deadlines (milestones) at AWL were often not met. I soon discovered that planning at AWL is a very big and difficult task, that a lot of different people are involved in the planning process, and that even more people have an opinion about planning. This made my research challenging and made defining a well demarcated scope of the project difficult. Finally, in conjunction with my supervisors, I decided to focus on the tactical planning phase, and in particular on the role that scientific methods can play in reducing the fluctuations in the capacity demand of various capacity groups and in reducing the cost of non-regular capacity.

With my report I hope to persuade the management of AWL to invest in upgrading their tactical planning function based on planning algorithms. The performed experiments show that AWL can benefit from employing algorithms for tactical planning and that both costs and planning effort can be significantly reduced.

I thank some people in particular without whom I could not have reached this result. Joachim Veldkamp, for introducing me to the tactical planning process and for helping me out with questions and opinions. Marcel van Dorp, for helping me out with programming issues in general, for helping me to get familiar with the planning data structure and for his efforts on retrieving and transposing data. Harald Lubbinge, for his input and for motivating me to go the extra mile. Moniek Nieuwenhuizen-Bouw, for generating reports on various kinds of (financial) data. Gerald De Boer, Ronnie Kuiper, and Dirk Everaarts, for their explanations, input, and expectations at the beginning of my project.

I also thank my AWL supervisors: Matthijs Leeuwangh and René van Tol, for their ideas, input, assessments and for giving me the opportunity to do the assignment at AWL in the first place. My University of Twente supervisors: Marco Schutten and Erwin Hans, for their time, criticism, and for helping me out when I got stuck. Finally, I thank my girlfriend Karin, my friends, and family for all of their support during the conduction of the research and in general.

Jeroen Evers

Enschede, November 2013

Summary

AWL-Techniek is a company that builds automated welding machines, mainly for production lines in the automotive industry. AWL builds the machines in projects, each project has its own characteristics, since requirements are often tailored to the customer. Various departments with a limited amount of worker hours available are necessary to complete the projects. The motive for this research is that the capacity requirements of various capacity groups fluctuate strongly over weeks. This causes unnecessary high costs for the arrangement of non-regular capacity (overtime, temporary personnel, or outsourcing), a lower average utilisation of regular capacity, and busy periods in demand peaks. During these busy periods internal deadlines are often not met, which makes the planning and scheduling of successive activities and projects difficult.

The objectives of this research are:

- To give insight into the current planning methodology.
- To advise on the applicability of recently developed methods and algorithms for planning, from scientific literature.
- To show the benefit of algorithms for planning at AWL.
- To make recommendations for the implementation of a new planning method.

In this research we focus on tactical planning, which is the planning of high-level activities in order to be able to estimate capacity requirements for the coming months. These tactical plans are input for operational scheduling and define when activities can start and should be finished. Currently, the tactical planner makes a project plan when a new project is acquired without the help of an algorithm and without re-planning active projects. This research shows that AWL can benefit from planning from a multi-project planning approach. Examples in this report show that it is practically impossible to plan multiple projects with multiple activities efficiently by hand, because of the complexity of the planning problem. In this research we define an efficient tactical multi-project plan as a plan that, given all restrictions, is a valid plan with a low amount of non-regular hours needed and a low degree of fluctuation in capacity requirements over time.

This report considers several approaches from the scientific literature. We extend one approach (ICPA) with a few steps, in order to make it suitable to cope with non-regular capacity restrictions. To our knowledge, this is the first non LP-based heuristic that is able to do this. This extension of ICPA is referred to in this report as Augmented ICPA.

We perform an experiment, in which we re-plan the activities of 18 projects. The results show that, for the considered problem instance, a saving of 45% on the cost of non-regular capacity required is reached if we compare the current tactical plan to the plan resulting from the best performing algorithm. We argue that AWL can obtain a saving of between 0.6 and 1 million € on a yearly basis by employing an algorithm for tactical planning (depending on the intake of projects, input for- and effectiveness of the algorithm, and AWL's ability to adhere to the resulting tactical plans). Other benefits of a new planning method are:

- Less time spent on familiarising non-regular personnel with AWL.
- Less time spent on planning.
- More flexible planning.
- Insight into the effects of (possible) strategic and tactical decisions.
- Higher utilisation of regular capacity.

In order to achieve the benefits of multi-project planning with an algorithm, AWL must take some steps:

- First of all, AWL should measure a set of KPIs (proposed in this report) to able to say something about the performance of operations and of a (tactical) plan.

- AWL should eliminate ambiguity in their data and consequently adhere to strict rules, in order to be able to provide standardised and complete input data for a new planning system. Certain data needed for the proper employment of an algorithm is currently not available at AWL. An important element is the maximum non-regular capacity restrictions of the various capacity groups.
- In order to be able to plan from a multi-project perspective, a central tactical planning function should be responsible for the tactical project plan, also during the execution of the project. This way, the central planning function can manage the portfolio of projects and efficiently allocate capacity to project activities to guard the interests of AWL as a whole.

When AWL completes these steps, some experienced advanced planning software providers should be contacted and the possibilities of building a planning package tailored to AWL should be investigated. It is important to create support and trust in a new planning system; this report also provides some recommendations to this end.

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Chapter 1: Introduction

This chapter provides an introduction to this report and the conducted research at AWL. First, Section 1.1 introduces AWL, the company at which the research takes place. Section 1.2 explains the motives of AWL for initiating this research. Section 1.3 drafts the research objectives and defines the scope of the research. Section 1.4 gives the research questions, based on the perceived problems and the research objectives. These research questions also serve as the backbone of this report; therefore, Section 1.4 also lays out the structure of the report.

1.1 Company Introduction: AWL

This section briefly introduces the company where the research takes place. AWL Techniek BV is a Dutch company based in Harderwijk.

AWL specialises in the designing, building, and delivering state-of-the-art automated welding solutions. AWL draws from a broad portfolio of machines and they meet customer specific requirements. In 2012, about 80% of AWL's customers were suppliers to the automotive industry (machines used for, e.g., producing seat back panels or car cross beams).

AWL has ±200 employees at their headquarters in Harderwijk and about 80 employees at their subsidiaries. In 2012, a turnover of over 50 million euro was achieved by integrating almost 200 welding robots divided over several projects. Companies such as Brose, Lear, and Johnson Controls are amongst AWL's biggest customers.

1.2 Research Motivation

This section explains various reasons that motivated AWL to start a research with the topic of planning.

AWL works on an engineer-to-order (ETO) basis. This means that each order is seen as a separate project. An ETO organisation designs and makes products fitting the specific needs of the customer, therefore the customer is willing to pay more. The downside is that ETO comes with higher costs, higher risks, and longer lead times (Hicks et al., 2000). In a pure ETO setting, every project is new and it is therefore hard to estimate durations of activities or even to exactly define the activities needed to reach a project's goals. Some characteristics of an ETO environment are high variability, many disruptions, a long engineering phase (Hans et al., 2007). These characteristics make planning at an ETO organisation especially difficult.

AWL virtually always meets deadlines agreed with the customer to finish a project. However, milestones set in the tactical plan of a project are often not met. This leads to a company-wide feeling that the planning of projects can be improved. Currently, AWL uses overtime or temporary workers (non-regular capacity) to make up for lost time, to make the customer deadline. This results in extra stress and costs for AWL. Furthermore, an increase in business for AWL in recent years has put pressure on AWL's resources. Therefore, AWL is interested to find out if and how its resources can be allocated more efficiently.

Meijerink (2003) performed a research at AWL, with a goal similar to the goal of this research. Meijerink's research goal was as follows:

"Giving insight into how well the act of capacity planning currently works at AWL and explore the potential benefits of using advanced, recently developed techniques or algorithms."

Section 2.5 discusses that many of the recommendations of Meijerink (2003) have not been followed up by AWL, ten years after Meijerink's research. AWL thinks that a new perspective on the planning issues can yield results that benefit the whole organisation.

Section 2.4 describes several problems and issues causing imperfect project plans. These issues are contributing to what we define as the main problem this research is concerned with:

"Internal deadlines as set in the project plan at AWL are often not met."

This results in extra costs for AWL, resulting from overtime and the hiring of temporary personnel. If milestones early in the project are not reached, the effect of extra costs is even higher, because consecutive activities (and thus milestones) are getting pinched. Furthermore, if activities are taking longer than planned, other projects are affected, because of occupied capacity.

1.3 Research Objectives & Scope

This section gives the objectives of this research and explains the boarders of the research, with a goal of providing a clear demarcation of what we investigate in this report. The research objectives are:

- To give insight into the current planning methodology. (Chapter 2)
- To advise on the applicability of recently developed methods and algorithms for planning, from scientific literature. (Chapter 3)
- To show the benefit of algorithms for planning at AWL. (Chapter 4)
- To make recommendations for the implementation of a new planning method. (Chapter 5)

For this research, we focus on the tactical level of planning, on rough-cut capacity planning. A tactical plan is a plan overseeing a time horizon of several months. In case of a multi-project organisation such as AWL, with projects with a duration of several months, the planning on project level can be seen as the tactical level. Rough-cut capacity planning is done at the tactical level of planning. Rough-cut capacity planning is planning high-level activities in the early stages of the project. The goal is to estimate the effects on resource capacities. With these estimations one can arrange non-regular capacity timely, make order acceptance decisions, and quote a reliable due date.

On the tactical level, planning is currently done from a single-project perspective, that is, projects are first planned in isolation and then the effects on capacity of various capacity groups are considered. Multi-project planning, in contrast to single-project planning, plans all activities of multiple projects at the same time. Multi-project planning can yield that the capacities of capacity groups are used more efficiently, reducing cost of non-regular capacity and reducing stress caused by demand peaks (Meijerink, 2003).

Currently, the differences between needed capacity over weeks are considerable. Furthermore, capacity checks are only done sporadically and over an aggregation of capacity groups. Tactical planning at AWL is done manually. Problems observed at the operational planning stage are partly caused by the inefficient way of planning at the tactical level. Periodical multi-project planning, including the re-planning of running projects based on an algorithm, is expected to yield a more consistent level workload for various capacity groups over time and reduce the need for non-regular capacity.

1.4 Research Questions

This section formulates the research questions. These research questions also set the structure of this report.

The research questions needed to reach the research objectives are:

Chapter 2: Current Situation

- In what setting does AWL and its tactical planning function operate? (Section 2.1)
- What is the current planning process? (Section 2.2)
- What is the performance of the tactical planning function at AWL? (Section 2.3)

- What causes unmet milestones? (Section 2.4)
- What are the lessons we can learn from Meijerink (2003)? (Section 2.5)
- What research direction is most suitable for this research and most promising for AWL? (Section 2.6)
- What is multi-project planning and why is it important? (Section 2.7)

Chapter 3: Literature Review

- How is the tactical planning problem observed at AWL referred to in the literature? (Section 3.1)
- What appropriate methods and algorithms can be found in the literature? (Section 3.2)

Chapter 4: Redesign Of Planning Process

- Which methods or algorithms do we select to look into further? (Section 4.1)
- How can we apply algorithms, in a relevant manner for AWL? (Section 4.2; Section 4.3)
- How do the methods and algorithms found in scientific literature perform? (Section 4.4; 4.5)
- How should the observations of the experiments be interpreted? (Section 4.6)

Chapter 5: Implementation

- In terms of data management, what must AWL do to accommodate a new tactical planning system? (Section 5.1)
- In terms of organisational changes, what must AWL do to accommodate a new tactical planning system? (Section 5.2)
- How does a new tactical planning system affect operational scheduling? (Section 5.3)
- What specifications must new tactical planning software have and what considerations should be taken into account when developing the software? (Section 5.4)
- What are the costs and challenges for (implementing) a new planning system? (Section 5.6)
- How should commitment for implementing the new tactical planning algorithm be realised? (Section 5.5; 5.7)

Chapter 6: Implications And Recommendations

- What are the implications of this research? (Section 6.1; Section 6.2)
- What recommendations can we give to AWL to reduce the number of unmet internal deadlines and to increase their productivity as a whole? (Section 6.3; Section 6.4)

Chapter 2: Current Situation

This chapter describes the current situation of the tactical planning function at AWL. Section 2.1 describes the business environment in which AWL operates, to understand what needs to be planned and against what restrictions. Section 2.2 elaborates on how the planning functions within AWL are arranged. Section 2.3 discusses the performance of the tactical planning function and how it should be measured. Section 2.4 gives a structured overview of planning problems at AWL. Section 2.5 discusses the recommendations made by Meijerink (2003) and discusses whether and how these recommendations have been handled by AWL. Section 2.6 elaborates on the research direction of this report. Section 2.7 explains the importance of multi-project planning and draws conclusions from the other sections in this chapter.

2.1 Setting

This section describes the setting that AWL operates in, to understand what needs to be planned and against what restrictions imposed by this environment. Section 2.1.1 discusses the products AWL makes and analyses the industry for which AWL makes its products. Section 2.1.2 discusses AIM100, an interdepartmental improvement project with a goal of working more efficiently. Section 2.1.3 describes the flow of a project through the company, along the various departments.

2.1.1 Products & Markets

This section discusses what types of products AWL makes, for what markets it makes products, and analyses the industry that AWL operates in. The section concludes with five requirement categories of AWL's customers, to define the wider environment in which AWL's processes take place.

AWL engineers and builds welding machines that are custom made to fit the customers wishes. AWL has experience in constructing machines that produce products for construction, warehousing, packaging, and enclosures. The largest part of AWL's clientele is active in the automotive industry. In 2012, about 80% of AWL's production was meant for the automotive industry. Mostly, the customers of AWL are suppliers to car manufacturers, such as Opel and Audi. Examples of parts that AWL's machines make are car seats, car cross beams, fuel tanks, air bag modules, bumpers, and exhausts.

The automotive industry has its own set of characteristics. First of all, the quality of all parts in a car should be impeccable. The safety of drivers and the reputation of car manufacturers are at stake. Therefore, AWL needs to produce machines that deliver constant quality products and the margins on the dimensions of parts are slight.

Mostly, cars are produced in high volume, which means that customers of AWL require machines that deliver parts at a steady pace. In the automotive industry, it is common to express the speed of machinery in terms of the takt time, which is the time between the production of two parts (at a constant rate).

In the automotive industry deadlines throughout the supply chain are important. This is because, often, the car manufacturer has already announced a new type of car, when the supply chain has not completely been shaped. This yields that AWL's customers require machines on short notice relative to the needed time to engineer and produce the machine. Sometimes, a car manufacturer already has customers for its cars before AWL has made a machine for the production of some part. This is why customer deadlines are hard restrictions at AWL and everything is done to ensure that customer deadlines are met.

As in most industries, cost plays a role in choosing between suppliers. If a competitor of AWL can deliver a machine with the same specifications and the same quality, the price is the decisive differentiator to gain a customer. Cost is not the main focus point of AWL, customer service is.

Customer service entails several things. The most important component of customer service for AWL is its ability to meet specific customer requirements (Engineer-to-order). Therefore, customers can change specifications during the execution of the project if necessary. AWL has a service department that is specialised in servicing (maintenance and repairs) for customers.

2.1.2 AIM100

This section discusses the role of the Lean Manufacturing philosophy adopted by AWL and how this philosophy relates to the planning function. It is important to mention the philosophy of AWL as it is part of the environment in which a planning system should be set up and a planning system should be in line with this philosophy.

A recently developed representation of the core values and main focus points for AWL is the so-called AIM100 House (*Figure 1*). AIM stands for “AWL In Motion”. The depiction of the essence of a company’s characteristics in the form of a house is common in a Lean Manufacturing or Toyota Production System (TPS) based organisation. AIM 100 is the name of a project, ran by a multi-disciplinary project team.

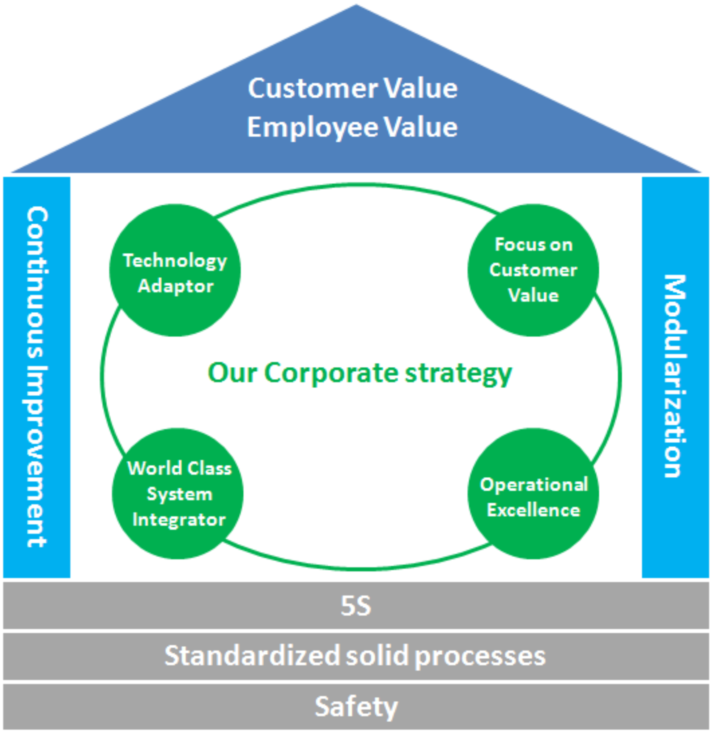


Figure 1: Aim 100 House

AWL summarises the five goals of AIM 100 as follows:

- 100% performance
- 100% right
- 100% happy employees
- 100% customer satisfaction
- 100 million euro turnover

These goals are guidelines and motivators for the whole organisation, to put in their best effort and to avoid mistakes. A focus on the customer and prevention of mistakes causes a high customer satisfaction. The financial goal is a turnover of 100 million euro in 2018. In 2012 the turnover was 50 million euro. The aim is to reach this financial goal without notable expansion of capacity.

The AIM100 House in *Figure 1* is an extension of the corporate strategy. The fundament of the House depicts the prerequisites for a good performance of AWL’s operations. Safety comes first in everything AWL does. An aim is to standardise processes more. The idea is to not engineer all projects from scratch, but to work more with standard modules. Currently, Engineering engineers everything, even parts that have already been engineered in the past. They make small improvements to the design, but this is time consuming and thus costly. Mostly, these small improvements go unnoticed by the customer, so they have no added value. Another aspect of the fundament of the AWL organisation is the 5S philosophy: sorting, setting in order of flow, systematic cleaning, standardising, and sustaining.

When the aspects of the fundament of AIM100 are warranted, AWL should indulge in continuous improvement (or Kaizen), which is a Lean Manufacturing concept to incrementally improve processes. Furthermore, further possibilities for modularisation are examined. Mistakes are reduced when employees of AWL work in a more standardised manner, so that repetitiveness of tasks causes employees to gain experience in doing the tasks. Finally, everything at AWL is done with the well-being of the employee and the customer in mind.

This research should be seen as an extension of the AIM100 activities at AWL. The goal is to improve and standardise the tactical planning process. This results in a more stable demand for capacity of various capacity groups, resulting in a better utilisation of capacity, and thus more available capacity to accept more projects and increase turnover.

2.1.3 Project Composition

This section explains which project activities AWL distinguishes at the tactical planning level. The various capacity groups are also listed. This section also describes how and when milestones (internal deadlines) are set.

In 2012, AWL finished 41 projects. Based on data from projects of the last 2 years, the average duration of a project is 258 days (8.6 months) or 0.7 years, with a standard deviation of 138 days. Little's Law states: *Cycle Time x Throughput=Work In Process*. This means that on average (0.7*41) about 29 projects are actively worked on at one moment in time (which is at various stages: at engineering, on the assembly floor in Harderwijk or in the Czech Republic, or at a customer).

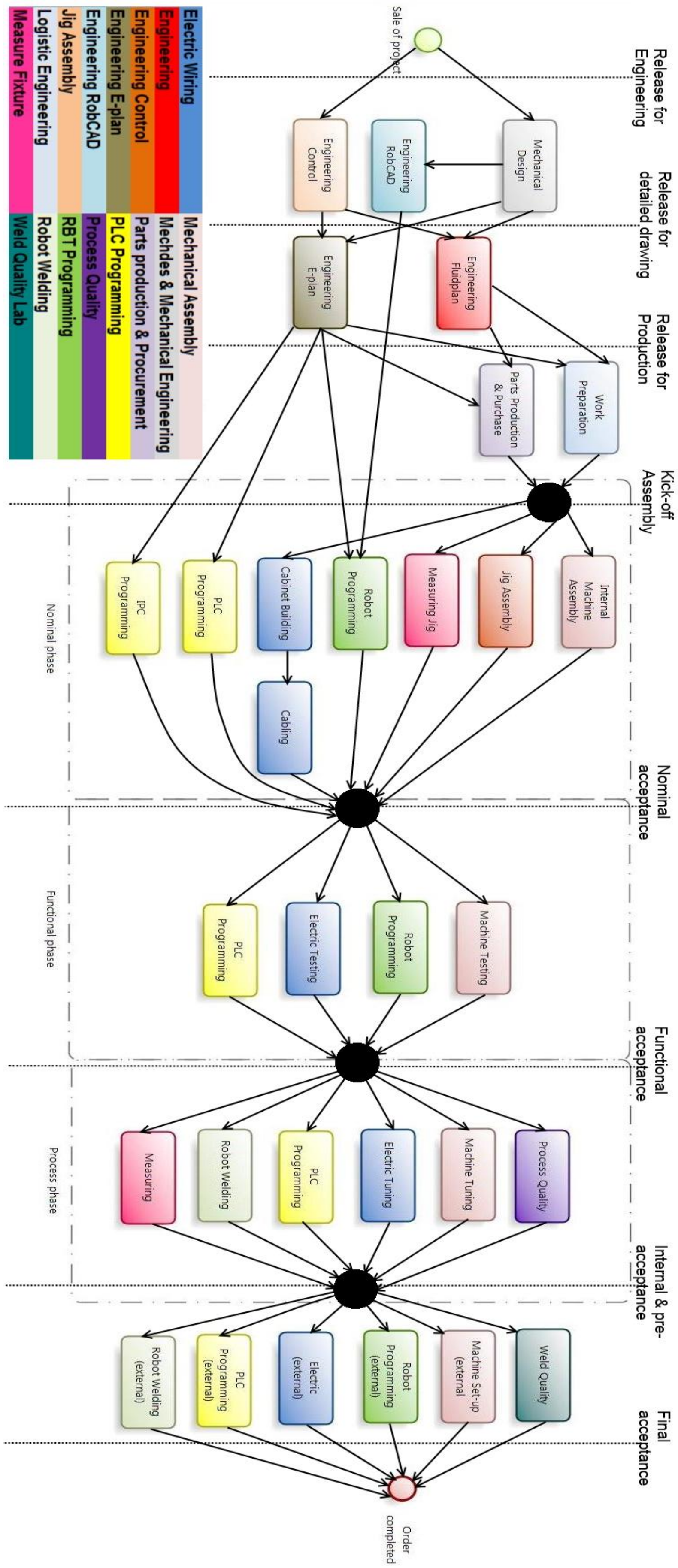
Appendix I lists the capacity groups that AWL distinguishes in a table, together with their current regular capacity, maximum non-regular capacity, cost of non-regular capacity, and the time period needed for arranging non-regular capacity. These capacity groups are not always homogeneous, in the sense that not all staff have the same capabilities. For example, four brands of robots, with different programming methods are distinguished. Not all robot programmers are familiar with all brands.

Figure 2 on the next page displays the various activities in a project network. The figure displays the precedence relations between activities, which means activities cannot start before all predecessors are finished. *Figure 2* also displays which capacity group performs the activity.

Each activity is performed by only one capacity group. Each activity implies a certain workload, which is the number of man hours that needs to be spent to complete the activity. The workload of activities differ per project. AWL makes a distinction between estimated workload, team hours, and actual hours. The estimated workload is the workload estimated per activity by the calculation department, on which the tactical plan is based. The team hours are the workload estimated by the team or capacity group themselves. This estimation is usually done a few weeks before the activity starts. The actual hours are the actual number of hours spent on an activity.

Figure 2 also displays the milestones by the dotted vertical lines. Before activities right of such a line can start, all activities left of the line have to be finished. It is remarkable that in the earlier stages of the project, sometimes activities are allowed to start by the precedence relation restrictions, but not according to the milestone restrictions.

Figure 2: Project network



2.2 Current Planning Process

This section explains who is responsible for what planning task at AWL. Section 2.2.1 discusses a hierarchical project planning and control framework, which gives an overview of the different planning responsibilities within a multi-project organisation. Section 2.2.2 provides an insight into the current planning process. Next, Section 2.2.3 goes deeper into the tactical planning process at AWL, leading to a rough-cut project plan.

2.2.1 Hierarchical Project Planning And Control Framework

This section discusses the hierarchical project planning and control framework by Hans et al.(2007). This section also gives an overview of where the planning responsibilities lie at AWL.

Whereas most hierarchical planning frameworks focus on more standardised manufacturing settings, the hierarchical project planning framework by Hans et al. (2007) is used to position planning methods for multi-project planning under uncertainty. Other hierarchical planning frameworks that have been proposed for project-driven organisations do not make a distinction between the different objectives at the various managerial levels. Moreover, other frameworks focussed on project-driven organisations do not sufficiently account for variability and the integration of technological planning, capacity planning, and material coordination. *Figure 3* depicts the framework by Hans et al. (2007).

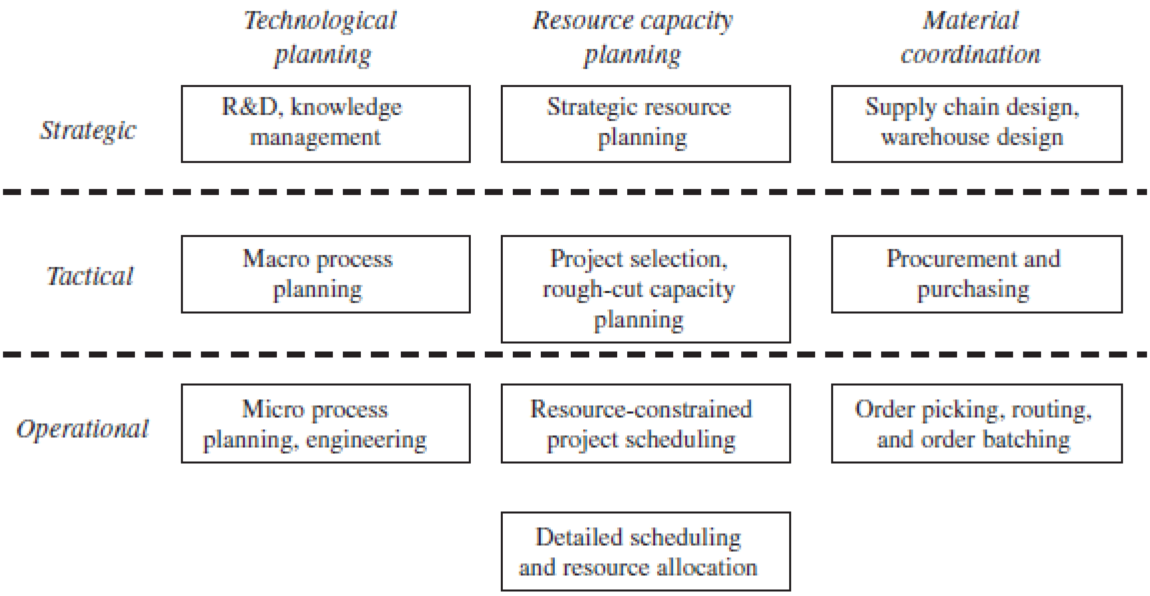


Figure 3: Hierarchical project planning and control framework (Hans et al., 2007)

Figure 3 distinguishes three hierarchical levels: strategic, tactical and operational. Strategic planning functions are usually the responsibility of high-level management in an organisation. A strategic plan lays out the long term vision for the organisation. A strategic plan is a high-level representation of how an organisation will achieve its goals over a period of years. Decisions on the strategic hierarchical level include expanding fixed capacity or the decision to change the product portfolio, based on a long-term forecast of demand or of market developments.

Tactical resource capacity planning is partly based on forecasted demand, and partly on known demand. Tactical planning allocates the available capacity to the available projects. At this stage the regular capacity is fixed, but non-regular capacity can still be arranged against additional costs. In case of a multi-project organisation such as AWL, with projects with a duration of several months, the multi-project planning is seen as the tactical level. The objectives of tactical planning are to be able to estimate a due date of the project, to estimate the effect on various capacity groups, to determine milestones (intermediary project deadlines) and to determine an estimate of the needed (non-regular) capacity. The tactical planning function is often undervalued, as it is less alluring than laying down company-wide goals on the strategic level, and its results are less tangible and immediate than the results of an operational schedule.

The operational level is concerned with the short term scheduling of activities. At this stage, the scheduler knows with a high degree of certainty what activities need to be done and what the expected workload of the activities is. Off-line operational scheduling is concerned with planning which activities are done be whom, in what order, and/or when. On-line scheduling is the monitoring of the process, and, if necessary, adjusting to deviations from the off-line plan when they occur.

Figure 3 distinguishes three functional planning areas: technological planning, resource capacity planning, and material coordination. The technological planning area is concerned with the development and maintenance of knowledge and technology within an organisation. The resource capacity functions are concerned with the management of renewable capacity, that is, increasing, decreasing, and assigning capacity of resources. The material coordination functions are concerned with the procurement, the storage, and the flow through the supply-chain or the factory, of non-renewable resources (materials and sub-assemblies). This research is concerned with the resource capacity planning.

At AWL, the activities that are distinguished in the framework, under resource capacity planning, are responsibilities of the following individuals or departments:

Strategic resource planning:

- Chief operating officer, Manager Project Management, Manager Logistics, Manager Assembly, Manager Process Quality

Project selection:

- Sales department

Rough-cut capacity planning:

- Planner

Resource-constrained project scheduling:

- Project leader

Detailed scheduling and resource allocation:

- Department heads: Coordinator Jig Assembling, Team Leader Planning & Project Coordinators (Assembly department), Technical Coordinator Robotics, Technical Coordinator Controls Department, Service Coordinator, Manager Operational Engineering, Manager Process Quality

Project selection is, in principle, a task of Sales. The planner makes the plan on which this decision is partially based. Sales makes the project selection decision in deliberation with the planner, the logistic manager and the actors responsible for detailed scheduling and resource allocation. If perceived necessary, also the actors on the strategic resource planning level are consulted.

At AWL, the difference between the rough-cut capacity plan and the resource-constrained schedule is slight. Project leaders only change the plan made by the tactical planner, when unforeseen setbacks occur (e.g. tardy delivery of parts). Section 2.2.3 explains that a tactical plan is made twice, first to quote a due date to the customer, and then a somewhat more detailed version after the acquisition of project. The project usually almost immediately starts, and even after the engineering phase(s), the tactical project plan is not revised (unless obvious problems surface). In terms of the framework presented in *Figure 3*, at AWL, the resource-constrained project scheduling phase is skipped or merged with the rough-cut capacity planning stage of projects.

The actors in charge of detailed scheduling and resource allocation are responsible for arranging non-regular capacity in the form of temporary workers, if they see the need. This is possible for most capacity groups, because the time span in which non-regular capacity can be arranged is relatively short (such as described in *Table 11*, *Appendix I*). Whereas, in literature, the hiring of non-regular capacity is often seen as a possibility on the tactical stage only (Hans et al., 2007; De Boer, 1998), there is an advantage in letting department schedulers arrange non-regular capacity, as they can better estimate and weigh the needs of the specific department and the (dis)advantages of various options for non-regular capacity. The actors in charge of detailed scheduling and resource allocation are also responsible for shop floor control, i.e., the monitoring of the processes and responding to unforeseen activity or delays.

There is a distinction between rough-cut capacity planning (at the tactical level) and resource-constrained project scheduling (at the operational level). There is less information available at the tactical level than at the operational level (De Boer, 1998). There is a gap in information about necessary detailed activities, activity durations, resource availability, or material requirements. This gap is especially apparent in an ETO organisation. After the engineering phase, a lot more information is available about the exact content of and the technological constraints regarding the detailed activities.

Another difference between rough-cut capacity planning and resource-constrained project scheduling is the larger flexibility at tactical level, e.g. to increase capacity. Gradually more information becomes available, when the starting time of an activity comes closer. These differences between rough-cut capacity planning and resource-constrained project scheduling yield that the approaches of making plans at these different levels should be different. A tactical planning methodology should utilise the flexibility present at the tactical stage of project planning. Furthermore, a tactical schedule should not be overly detailed, because the information make a detailed plan is not present at the tactical stage. For instance, at the tactical stage it is sufficient to plan an aggregation of activities as one, because details about the more detailed activities are not exactly known yet.

2.2.2 Planning Process

This section describes the current planning process at AWL, from the first RFQ of the customer to the operational, day-to-day planning at various departments. *Figure 4* depicts this process.

When Sales negotiates with a customer about a project, they need an estimation of the throughput time and an estimation of the cost price.

At Quotation Engineering, the technical knowledge and experience is present to predict the various steps necessary for the new project. This prediction is based on a draft of the specifications made by Sales and the customer.

Based on this step-by-step plan, the calculation department estimates the cost of materials and (the cost of) workload (labour hours) necessary per department and per activity. For this, the calculation department uses an algorithm based on experiences from previous projects.

Based on the workload per activity, the planner builds a tactical plan for the project. The planner decides how work content is spread and determines the estimated duration of the various activities. The planner then checks the effect of his plan on the capacity of the various capacity groups. If the tactical planner perceives that the sum of needed plus taken capacity (by other projects) exceeds the capacity of one or more capacity groups too much, the planner might try to manually adjust the draft tactical planning. The decision of whether capacity is exceeded too much, is currently a subjective decision of the tactical planner. This decision is made based on past experience and consultation of departments. Furthermore, there is always a trade-off between how much capacity may be exceeded and the perceived importance of a project.

If necessary, a discussion between the planner, Sales, and potentially relevant department managers is set-up to make a choice between exceeding capacity and doing the project, or not exceeding capacity and not doing the project. If internal agreement is reached, the negotiations between the customer and AWL continue (armed with a cost price estimation and a deadline proposition).

If agreement between the customer and AWL is reached, a similar process from Quotation Engineering to the planner is initiated based on the “as-sold” specifications. Quotation Engineering, Calculation, and the planner are now more thorough and detailed in their estimates, because the project will actually be executed. In this phase, the planner collaborates closely with department heads, to keep them in the loop and to get mutual agreement on the proposed planning. Section 2.2.3 describes the tactical planning phase in more detail.

When the tactical plan is finished, the project is carried over to a project leader. From this point, the project leader is responsible for achieving the project goals and for adjustment of the tactical plan if necessary. The budgeted hours are reassessed by the team responsible for a task. These reassessed hours are, however, no reason to change the project plan.

The operational, day-to-day planning is done by the department heads. This is done using a software application called the AWL-planner. In this software application, the hours budgeted for a human capacity group for a certain week or day are shown as “dummy-hours” and are to be assigned to specific persons (e.g. a mechanic). The amount of “dummy-hours” can easily be adjusted by the department schedulers. However, a deviation of the team hours of more than 10% needs to be brought to the attention of the project leader.

If new insights occur during the planning or execution phase of a project, the various actors might send relevant information upstream. In general, there are no institutionalised rules for this communication, or under what circumstances information should be shared.

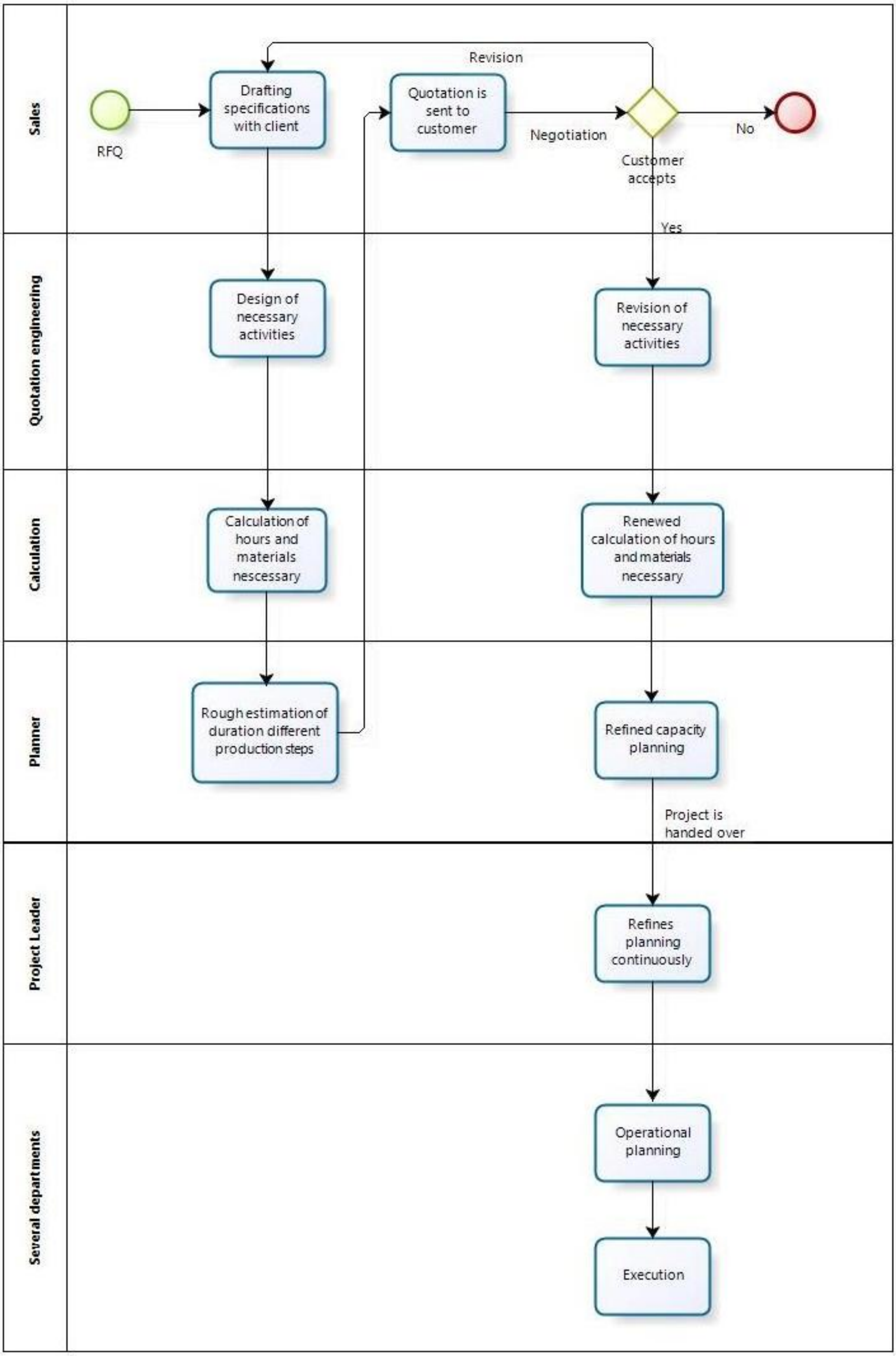


Figure 4: Planning process

2.2.3 Tactical Planning Process

This section discusses the tactical planning process at AWL. *Figure 4* shows that the planner makes a project plan twice. First, for a rough capacity check and an estimation of the lead time. Then, when Sales acquires a project and more details are known about the project, the planner makes a more detailed project plan. The processes that lead to the two types of project plans are similar, with the difference that the second time more time is spent on the plan. More time is spent on consultation of various departments, to make sure the plan is sound in terms of expected workload and precedence relations, and to create consensus.

Input for the planning process is an Excel-sheet from Calculation. This Excel-sheet gives an overview of activities and their expected workloads. From Sales, one or more deadlines are known. The final deadline of the project is known, but agreements can still be made on when AWL starts rebuilding the machine at the customer, or when the first test-series of parts from the machine should be ready.

The planner plans the activities backwards from the deadline. Some activities can only be done by one person, e.g. PLC or Robot Programming. For these activities, the planner plans one employee full time (so 40 hours per week), easily determining the lead time of the activity. For activities where more than one person can work at the same time, the planner estimates based on drawings how many employees can work on a machine at a time without loss of worker efficiency. The planner plans based on this number. The disadvantage of planning by spreading the workload evenly at the tactical level, is that it fails to fully utilise flexibility available at that stage.

Next, the planner checks the capacity graph of various capacity groups and checks the effect of the new project on the workload of the various (aggregated) capacity groups. *Figure 5* gives an example of such a graph. In this figure, the x-axis gives the week numbers and the y-axis gives amounts of workload in hours per week. The green line gives the available number of hours per week (fixed plus already arranged variable capacity), the red line gives the needed number of hours per week to perform already acquired projects, and the blue line is the red line plus the number of hours needed to perform projects which are expected to be acquired or are under consideration.

The expected workload may exceed the capacity, because of the ability to hire temporary workers, because the project is regarded as important, and because the operational planners are expected to “make it work”. The planner communicates his plan to the various stakeholders within AWL, mainly the support of the department line managers is important. When a plan is finished and agreed upon, the project is carried over to a project leader.

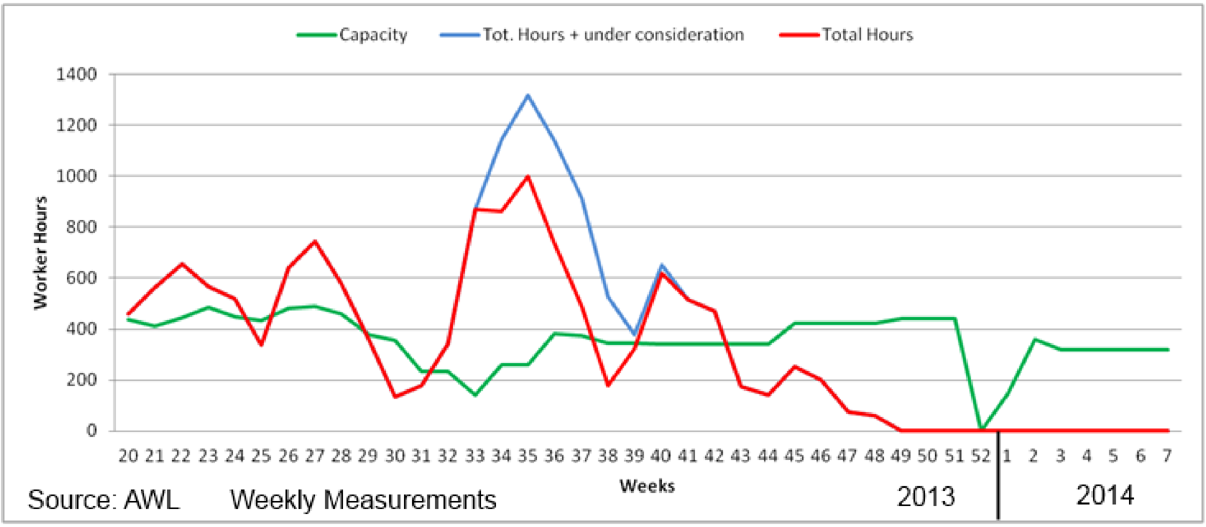


Figure 5: Demand fluctuation at the jig assembly department

2.3 Performance

This section discusses how the performance of AWL's tactical planning function should be measured. This section provides a stakeholder analysis to determine what requirements a tactical plan must meet according to each stakeholder. The stakes held by stakeholders are used to define KPIs. AWL should use these KPIs to measure the performance of the tactical planning function and of operations in general.

Table 1 describes the stakeholders that we distinguish within AWL and the requirements that should be met in a tactical plan according to the stakeholders. We determined these stakes by discussions with stakeholders. We place the stakes of the customers under Sales and the Board of directors, because these are AWL's internal stakeholders, that are most directly concerned with the customer's interests. *Table 1* shows the KPIs that are linked to a stake between brackets, we discuss these KPIs later in this section.

Stakeholder	Stakes
Board of directors	* Cost of temporary workers/ non-regular capacity should be minimised (*KPI 5*)
	* Customer should be satisfied with final product (*KPI 7)*
	* Customer deadline should be met (*KPI 1**, *KPI 2**)
	* Overall output of the system should be maximised (*KPI 6*)
	* Project team composition should not be changed often, to create a sense of ownership amongst workers, which will benefit quality *(KPI 11)*
Sales	* Customer should be satisfied with final product (*KPI 7)*
	* Customer deadline should be met (*KPI 1**, *KPI 2**)
Work preparation	* Available time should be sufficient to make good deals with suppliers (*KPI 7, KPI 8)*
Finance	* Difference between budget and actual expenditure should be minimised (*KPI 8, KPI 9)*
	* Cost of temporary workers/ non-regular capacity should be minimised (*KPI 5*)
Tactical planner	* Plan should be accepted by all stakeholders
	* Time needed for tactical planning should be minimised (*KPI 10*)
Project management	* There should be enough time to deliver quality work (*KPI 7*)
	* Milestones should be met (*KPI 1, 2*)
	* Revisions of tactical plan should be minimised (*KPI 3, 4*)
Operational schedulers	* Short term changes to plan should be minimised (*KPI 1, 2, 3, 4*)
	* Variability in capacity demand should be minimised (*KPI 6*)
	* Time needed for operational scheduling should be minimised (*KPI 10*)
Workers	* There should be enough time to deliver quality work (*KPI 7)*
	* Preceding activities should contain no mistakes (*KPI 7)*
	* Overtime should be minimised (*KPI 5*)
	* Short term changes to personal schedules should be minimised (*KPI 1, 2,3, 4*)
	* Workload should be evenly divided over time (*KPI 6*)

Table 1: Stakeholder analysis linked to KPIs

The large number of stakes held by various actors within AWL should make the tactical planning function a central function within the company, whilst at the same time meeting and balancing all the stakes is a difficult task for the tactical planner. Some stakes are obviously antithetic, for instance: the wish of Sales to minimise the throughput time of a project and the need of workers to have enough time to deliver quality work.

There is a need for measurable performance indicators to make the trade-offs insightful, to be able to receive feedback on the performance of an executed tactical plan, and to draw lessons for the future from this feedback. *Appendix II* describes formulas for calculating the performances on KPIs. We define the following KPIs:

- **KPI 1 & 2**

A goal of project management is to meet milestones, which are the intermediate deadlines set in a project. This goal is in line with the wish of operational schedulers that short term changes in a plan are minimised. The extent to which milestones are met is measured by the number of milestones not met (*KPI 1*) or the sum of time units by which milestones are not met (*KPI 2*).

- **KPI 1* & 2***

Although the customer deadline is a hard restriction, it does not mean they are always met. Therefore, we also have to have separate KPIs for the final deadline. These final deadline KPIs are denoted by *KPI 1** and *KPI 2**.

- **KPI 3 & 4**

A related KPI is the number of revisions of a project plan. A revision of a project plan is defined as a postponement of a milestone by more than one week (compared to the original tactical plan), because of unforeseen setbacks. We distinguish between how many milestones are postponed (*KPI 3*) and by how much (*KPI 4*). If the postponement of a milestone early in a project causes consecutive milestones to be postponed, we measure the total number of postponed milestones.

- **KPI 5**

The total cost of non-regular capacity used (*KPI 5*) should be minimised. Various non-regular capacity types per capacity group are distinguished (e.g. overtime, capacity from CZ, temporary workers from company A, temporary workers from company B, etc.). These various capacity types imply different costs.

- **KPI 6**

Reduction of fluctuations in capacity demand for capacity groups is favourable. We define this as either the average deviation of needed capacity from the average capacity demand, or the deviation for this week's capacity demand from last week's capacity demand (*KPI 6*). In this research we use both measures.

- **KPI 7**

The quality of performed work should be good. The duration of an activity can increase if the quality delivered by preceding activities is not good. It is, however, difficult to define or measure the quality of a performed task at various departments at AWL. An option is that the performance of an activity is measured by how much delay of successive activities is caused by mistakes of the activity (*KPI 7*). There is, however, a high level of subjectivity in this measure.

- **KPI 8 & 9**

Part of a tactical plan is a budget for the project, which is used to control costs. The degree to which is deviated from the budget is a KPI for the tactical planning stage. The difference between budgeted expenses and actual expenses can be measured in two distinct ways. First, the sum of the difference between total budget and actual total expenditure should be minimised (*KPI 8*). A second manner is the sum of the absolute difference between budget and expenditure per time unit (*KPI 9*). So, *KPI 9* looks at budgets on a micro-level, which is necessary to control costs during a project. It is also a problem if the actual costs of an activity in a week is lower than the budgeted costs, because this means that the budget was inaccurate.

- **KPI 10**

The time spent on operational and tactical planning activities (*KPI 10*) should be minimised. A planner's time is costly and saved time can be spent elsewhere.

- **KPI 11**

The number of changes in a project team (*KPI 11*) should be kept to a minimum. Some employees at AWL are linked to a project. A project has a Salesman, Project Leader, Project Coordinator, Logistic Engineer, ROBCAD Engineer, Project Engineer, PLC Technician, Robot Technician, and a Head Mechanic. The goal is that these actors stay at the project for the entire duration of the project. Practice is, however, that due to changes in the tactical plan of one or more projects to which an actor is assigned, overlap occurs. This sometimes means that the actor has to be replaced at one of the projects he was assigned to. This has negative consequences, such as that the replacement has to catch up on the specifications and the status of the project. Another consequence is that it is harder to trace under whose responsibility mistakes have been made. A third consequence is that someone who is linked to a project for the full period of execution feels a connection to the project and feels a sense of ownership, which benefits the quality of the project.

One stake in *Table 1* is not covered by a KPI, namely the stake that a plan should be accepted by all stakeholders, because acceptation is difficult to measure. Furthermore, we believe that (apart from communication and management skills of the tactical planner) this should be realised by measuring, controlling, and defending the stakes of all stakeholders through the KPIs.

The statement derived from *Table 1*, that a higher throughput is realised through a level workload (*KPI 6*), needs further explanation. Both the blue and red lines in *Figure 6* have the same average amount of workload. The blue line displays a situation with high fluctuation in demand for hours of a certain capacity group. The red line displays a situation with low fluctuation in demand for hours of a certain capacity group. Suppose that we add a project with an average workload equal to the difference between the peaks of the red line and the green line (the capacity limit). The project fits in the situation of the red line (low capacity demand), but the capacity limit would be exceeded in the situation of the blue line (high capacity fluctuation). So, through levelling the workload of an organisation on the tactical planning level, available capacity can be better utilised.

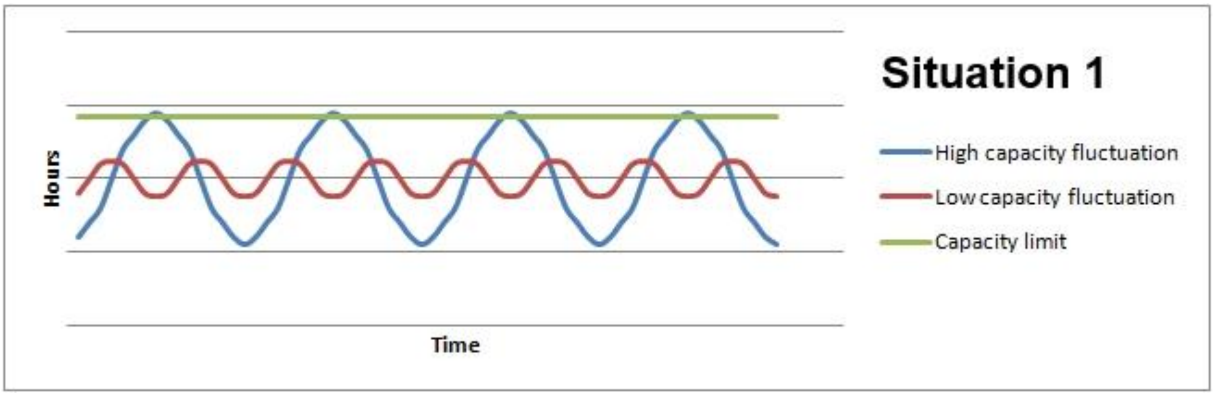


Figure 6: Level workload illustration 1

Figure 7 depicts a situation with lower regular capacity in comparison to *Figure 6*. There is now a need for non-regular capacity. We see that the situation with a high capacity requirement fluctuation (the blue line) needs more non-regular capacity (so higher costs) than the situation with low capacity requirement fluctuation to perform the same workload.

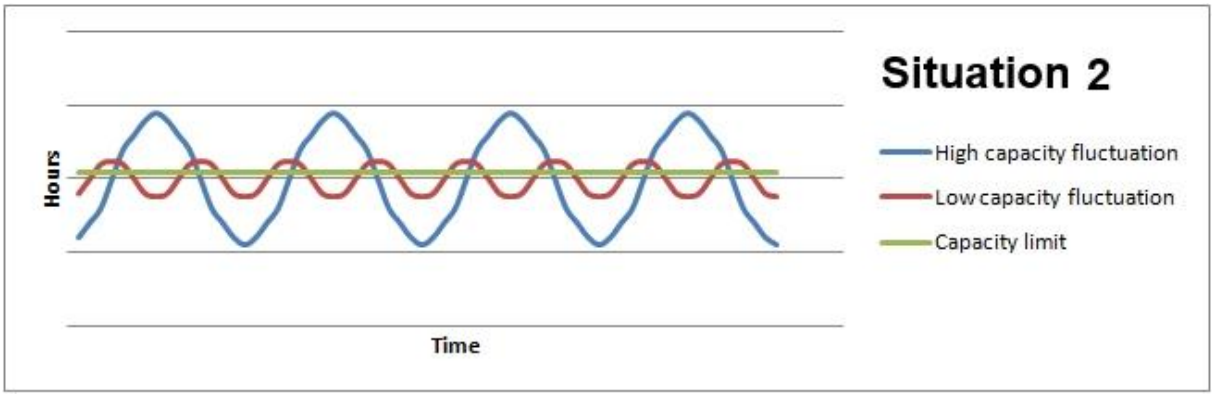


Figure 7: Level workload illustration 2

When new personnel is hired, training and familiarising new personnel with processes is time consuming. Therefore, a level workload over time is desirable, because this would mean that, in general, non-regular personnel needs to be hired for a longer consecutive period of time. Furthermore, it is easier to manage smaller groups of non-regular workers (Gademann & Schutten, 2005).

Also, the peaks of the blue lines in *Figure 6* and *Figure 7* mean that the utilisation of the capacity is relatively high at that point. When the utilisation increases in a system, without reduction of variability, the waiting times of activities increase exponentially and thus the cycle times of activities increase. For a further explanation we refer to Zijm (2003).

Table 2 shows whether KPIs are currently measured and, if so, *Appendix III* describes how AWL performs in terms of the KPI.

KPI 1 & KPI 2	Not measured
KPI 1* & KPI 2*	Not measured
KPI 3 & KPI 4	Not measured, but estimates available
KPI 5	Measured
KPI 6	Measured
KPI 7	Not measured
KPI 8 & KPI 9	Measured
KPI 10	Not measured, but estimates available
KPI 11	Not measured

Table 2: Current measurement of KPIs

Most data required for the KPIs is not available. In almost all cases, when AWL collects data required for a KPI, they do not use the data for performance measurement. Only *KPI 8* and *KPI 9* are actively monitored to be able to make statements about the performance of projects or departments. So, there is currently not a good insight into the performance of the tactical planning function. We recommend that the KPIs that are currently not recorded should be recorded. Also, all KPIs should be actively used to assess the performance of the tactical planning function and the overall performance of AWL.

2.4 Problems

This section provides an overview and analysis of perceived problems surrounding the broad subject of planning. Problems are mostly observed at the operational level, but some of these problems may partially be caused by sub-optimal tactical planning. Other problems may make making good decisions at the tactical planning level more difficult. The problems are the causes of unmet milestones. These perceived problems have been uncovered through conducting interviews with several AWL employees from various disciplines related to or affected by planning. We relate these problems to the KPIs from Section 2.3.

Planning is done based on throughput times, rather than based on available capacity
When the planner makes the rough-cut capacity plan for a project, he makes the plan in isolation. Afterwards, a check is done whether capacity of resources is exceeded. If perceived necessary, small manual changes are made to try and make the new project fit. No alterations in plans of running projects are made, which would be beneficial to the division of the workload at various capacity groups. Exceeding capacity at the tactical planning stage is not seen as a critical problem, because of the ability to hire temporary workers, because the project is regarded as important, and because the operational planners are expected to “make it work”. There is not always a quantitative insight into by how much fixed capacity can be exceeded per department and what the effects of exceeding fixed capacity are.

During the planning of a project, it is a choice to either take capacity or deadlines as a hard restriction. If the choice is to plan with deadlines as hard restrictions, then capacity limits can be increased (non-regular capacity can be added). Although the choice of planning with deadlines as hard restrictions is justified at AWL (because of the importance placed on deadlines by customers and the non-regular capacity), this choice comes with the danger of putting the demand for capacity groups too high.

When a project is carried over to a project leader and changes to the project plan are made by the project leader, this is done in isolation. Not planning taking regular and non-regular capacity directly into account results in high demand fluctuations (*KPI 6*) and high cost of non-regular capacity (*KPI 5*).

Operational scheduling and tactical planning is time consuming
In the current way of working, planning is time consuming (*KPI 10*). Operational schedulers have to assign available hours of individual workers to specific tasks. Also, when disruptions occur, the operational planning has to be altered by hand. The operational planner of the assembly department estimates he spends 15 to 20 hours a week planning (including alterations etc.). The jig assembly planner estimates he spends 2 hours a week on operational planning activities. For the tactical planner, tactical planning is a full-time function. This includes making plans for project, communicating and discussing plans, and altering plans when unforeseen setbacks occur.

Planning responsibilities are dispersed over several layers and departments
Planning a project at its various stages is spread over various departments and individuals. This creates a need for proper communication between these individuals, in order to avoid double work, ambiguities, or misunderstandings. Also, the complicated technical nature of projects renders that communication is important, for no individual has the knowledge to define each detailed project step necessary and estimate the workload. This adds to the time that is spent on planning (*KPI 10*). Multi-project planning in the current setting at AWL would be difficult, as the project plans are currently the responsibility of the project leader, rather than the project planner.

An overview of multiple projects simultaneously is not available in the operational scheduling software tool
AWL-planner is the name of the internally built operational scheduling software used. In this software environment the department line-managers have to assign the hours, as budgeted in the project plan, to individual workers. In the planning software, the scheduler sees the cumulative hours needed every week, for the coming months. The department line-managers can assign workers to tasks. The knowledge of whether a project is behind or in front of schedule is present at the project coordinators. The overview of what projects are behind or in front of schedule is not present for the schedulers. It is therefore difficult to make sound on-line scheduling decisions. If a project is behind schedule, the scheduler should get feedback from the floor (the project coordinator). This feedback is, however, not always given timely.

Planning methodology is the product of practice, rather than based on scientific literature
Planning at each stage is done manually at AWL (that is to say with computers, but without the help of algorithms). In scientific literature, algorithms exist that aid planning. It has been proved that these algorithms may yield considerably better results (in terms of e.g. throughput or levelled

workload) than when the same planning problem is solved by hand (Vaessens et al., 1996; Jozefowska et al., 2001; Hans et al., 2007; Herbots et al., 2008), especially when planning problems are complex, such as at AWL. Complexity stems (amongst others) from uncertainty of workload, parallel processes, multiple projects, and finite non-regular capacity. The main effect of scientific approaches to the planning approach would be a more levelled workload (*KPI 6*) and a lower cost through non-regular capacity (*KPI 5*).

Three different software packages are used
Three different software packages are needed to plan and schedule at AWL; these packages are Navision, MS-Projects, and the AWL-planner. Navision is the ERP-system used. Navision connects planning to other business functions, such as Procurement, Sales, and Finance. MS-projects is used to make the rough-cut capacity plan. The AWL-planner is used to schedule at operational level. Project leaders also use Excel to maintain and alter the tactical rough-cut capacity plan. MS-Projects and Navision are directly linked, and changes made are swiftly synchronised between the two packages. However, if changes are made in either software package, for a certain project, the information in the AWL-planner has to be updated and already assigned hours for the project are lost. That is why synchronisation of the various plans is sometimes skipped when changes are made to a project plan during the project (such as the postponement of milestones), resulting in ambiguous information. When synchronisation between software packages is done properly, this results in less work for planners (*KPI 10*).

Inexperienced employees often make mistakes
AWL has the ambition to give a chance to young technicians, but this strategy comes with the threat of more mistakes on the shop floor (*KPI 7*). Also, because of the fluctuations in capacity requirements (*KPI 6*) and the wish to reduce cost, AWL relies on temporary workers and interns. On average a third of workers in assembly is not in permanent employment at AWL; in jig assembly this number is about 50%. Often, mistakes are not detected immediately resulting in accumulating extra rework, depending on when the mistake surfaces. There is currently no objective insight in the effects of employing inexperienced workers and temporary workers on the quality and the duration of work. Of course, experienced employees also make mistakes, but the general feeling at AWL is that inexperience is a big source of mistakes, quality deficiencies, and rework.

Competences of employees are not mapped
Competences of employees are not mapped, in ,e.g., a staff capability matrix. For example, not all robot programmers can program every robot, due to the existence of four different brands of robots (four different programming languages). Often these competences are known by heart by the department line-managers, but the lack of documentation leads to problems when for instance a line-manager is replaced. Also, the lack of mapping competences makes it hard to manage the available competences in the organisation. Currently, competences of employees are not actively managed, creating bottlenecks for planning.

Several departments have different stakes when it comes to a project plan
Various departments have different ideas of what a good plan is, which Section 2.3 describes. Sales is interested in a short lead time and a low cost price of a project, so that they can negotiate a good deal with a customer. On the other hand, shop floor workers would like to have some more time do their job, so they can focus on the quality of the project and so they would not have to work under a lot of pressure. In their turn Procurement needs time to negotiate a good deal with suppliers and make sure materials arrive on time. This force field puts pressure on the Calculation department, the planner, and the project leaders. They have to keep in mind everyone's interest, possibly making their jobs of making a sound planning more difficult.

Milestones are not seen as hard deadlines
Milestones are not seen as hard deadlines, rather they are often perceived as an indication on when to finish a project. The observation that AWL does not keep track of whether milestones are met for various activities or departments (*KPI 1 & 2*), displays a lack of urgency when it comes to milestones. Milestones are an important tool for planners. When a milestone is not met,

the planning of consecutive activities or departments is obsolete. Consecutive activities need to be re-planned, imposing all kind of constraints, often triggering delays in other projects as well. For instance, if a head mechanic is scheduled to start on a new project next week, but his current project is delayed by two weeks, then this imposes serious problems for (the planning of) the new project.

There is fluctuation in customer demand

A cause of the fluctuation in demand (*KPI 6*) for capacity groups is irregular customer demand. *Figure 8* depicts the irregular customer demand, for 2009 to 2011. The numbers on the y-axis are left out, because this is classified information and not relevant to make our point. The measure on the y-axis is in euro; the cumulative price of projects acquired in a month. We assume this measure is an estimate for the relative magnitude of the workload required.

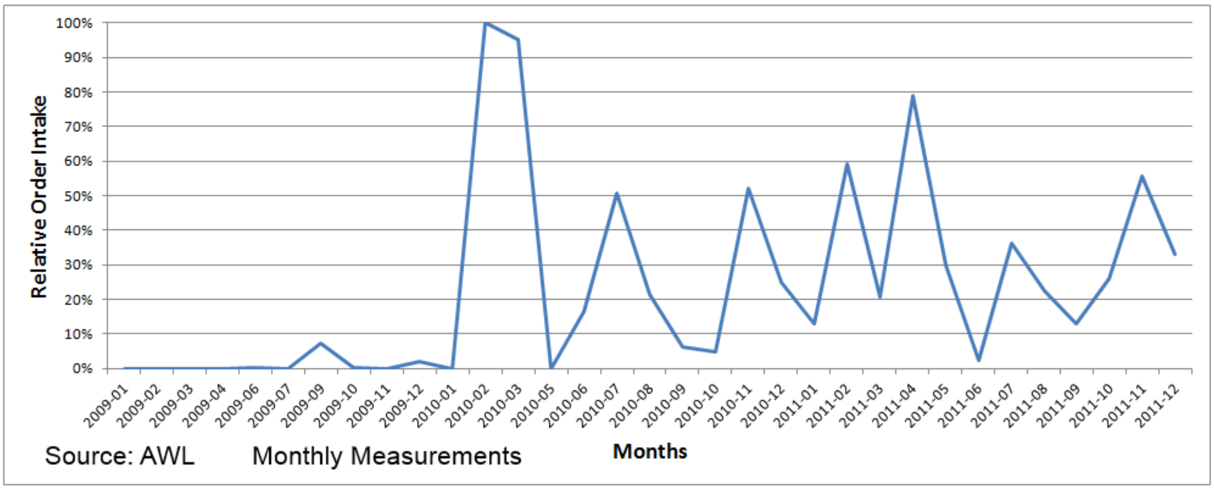


Figure 8: Order intake fluctuation

The peaks are caused by large individual projects or by projects that arrive in groups, because e.g. a car manufacturer introduces a new model, causing that various first-tier suppliers need new equipment at the same time. The irregular demand makes it more difficult to level the demand at various capacity groups (*KPI 6*).

The actual workload of various activities deviates from the estimated workload

It is inherent to ETO that the durations of several process steps are hard to predict. This makes planning difficult. Currently, the variability of activity durations is not taken into account when planning (e.g. in the form of buffers). There is more uncertainty at the tactical stage, in comparison to the operational stage. There are two main causes of uncertainty (Hans et al., 2007):

- Detailed information on the project becomes available only gradually (at AWL e.g.: new insights after engineering, or modifications by the customer).
- Operational uncertainties on the shop floor (at AWL e.g.: staff is needed at the service department, having to drop their current work, or uncertain capabilities of temporary personnel).

It is especially difficult to estimate the workload of the activities where testing of (sub-) assemblies is done, because considerably more man hours are needed if problems are found. *KPI 9* measures to what extent the actual workload of various activities deviate from the estimated workload. Another problem is the lack of feedback from various departments to the calculation department. If the calculation department were to have a better insights into the difference between their expected workload and the actual workload, they could make better estimates in the future. The responsibility of this feedback now lies with the project leaders (who do not do the scheduling) and the quality of the feedback differs from project leader to project leader.

Customers change specifications during the course of a project
Often customers change the specifications of projects. Possibly, this leads to the necessity of changing the composition of activities, to adding activities, or to rework. Allowing customers to change specifications is part of the customer-oriented philosophy at AWL, and little can be done to reduce this disruptive effect. There is no precise insight into how often these changes in specifications occur and what the precise effect on planning or milestones is.

Communication between departments is arduous
Scheduling is done per department, whereas the project planning is guarded per project. This means that various departments have to communicate about the progress of various projects. It is easy to lose the overview when all departments have to keep in touch about 15 projects. This issue is amplified by the lack of overview in the operational scheduling software. Monitoring the progress of individual projects is the responsibility of project leaders, but they do not do the operational scheduling. This means all (on average 15) project leaders have to keep in touch with all seven operational schedulers. The operational schedulers (department heads) are expected to channel this information and make sound on-line operational decisions, which is difficult.

Delivery of parts from customers or suppliers are often tardy
Not all materials coming in from customers or suppliers are on time. Last year, 89% of deliveries were delivered before the due date as agreed with the supplier; 77% of all materials needed, were present two days (grace period for internal handling and processing) before the start of the project. This last percentage includes materials that are not needed right away at the start of the project. It is, however, AWL's aim to have all required materials in-house before the start of assembly. This is done because management believes that tasks cannot be performed efficiently if during the performance of the task a team finds out that that parts are not available. A drawback of waiting until all materials are in-house, is that some parts have to be stored, occupying space for a certain period of time. Another disadvantage is that waiting for all parts to arrive, or starting with a less urgent activity, also is inefficient. Despite the known delivery performance of suppliers, the project plan assumes timely delivery. Tardy delivery can therefore postpone the earliest possible starting point of various activities, this impairs the prospect of meeting subsequent deadlines. Often, customers also have to deliver parts in order to tune and test a machine.

Sometimes quality of parts, subassemblies or engineering work is poor
Not all parts delivered by suppliers live up to the standards that are necessary. This renders the need for extra work or even re-ordering the parts. Furthermore, the quality of work from preceding departments and activities can be poor (*KPI 7*), causing rework and loss of time. The time that is lost caused by poor quality work of preceding departments, per department or in total, is not measured. The only exception is jig assembly, where lost time through influences from outside the department are recorded, together with the cause of the lost time.

KPIs related to planning performance are not always measured
Currently at AWL, there is no insight into how often milestones are not met, let alone by what margin. This is in part because of the ease with which milestones are postponed, the original milestones might not even be known at the end of a project. The lack of documenting this KPI leads to the problem that no one can judge the quality of the original plan and thus no lessons are learned for the future. It is unknown which milestones or at which departments the milestones are least frequently met. This particular problem makes it difficult to determine what the direct causes of unmet milestones are.

2.5 Meijerink's Recommendations
This section reviews the recommendations by Meijerink (2003) and describes to what extent these recommendations have been followed up. Furthermore, this section addresses the reasons behind not implementing recommendations. The goal of this section is to reveal potential pitfalls when trying to get recommendations implemented.

The various recommendations from Meijerink (2003) are listed below, with a short explanation of the effects of the recommendations:

One independent central planning function should be implemented, that controls and communicates all up-to-date information.
At the time of Meijerink's rapport there was one planning function that had to be combined with leading a department. Now there is one planner with planning as his main task. This is a direct effect of Meijerink's recommendations. Another difference between then and now is that today's tactical project plans are more detailed, distinguishing more activities. Furthermore, a difference is that the planner now makes a rough-cut tactical project plan during the sales phase of the project, to be able to predict a lead time and to get an idea of the effect on capacity groups.

Conclusion: AWL has followed the recommendation.

Uncertainty or variability should be taken into account in the planning methodology.
Not much has changed on this point, since 2003. Uncertainty was and is (largely) not taken into account when planning. At the tactical stage, all activities are planned at the earliest starting time based on the precedence relations and the expected duration of the activity. At the operational scheduling stage, workers are planned according to the expected hours needed for the project, so without slack. The only example of incorporating uncertainty is at PLC/Robot. For both the PLC and Robot programmers, one person is planned at 80% of his available hours, because the service department might need a programmer at some point.

Conclusion: This recommendation has not been followed up.

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.
Capacity checks were and are done after making the planning, comparing the available and needed capacity of various departments. The availability of capacity was and is not a hard restriction for the planner at AWL, because temporary workers can be used and because things seem to have a way of working out at operational level. So capacity checks were and are done only as a posterior check and capacity is not taken into account planning in some kind of algorithm or heuristic. No further research has been done investigating the applicability of various heuristics or algorithms for planning (until this research). Multi-project planning is not done, i.e. the re-planning of existing projects to free capacity for a new project (to level overall workload) is not done.

Conclusion: This recommendation has not been followed up.

Due to the complexity of multi-project planning at AWL, the planning function should be software aided.
As a result of this recommendation the AWL-planning software was internally developed. This application supports the operational scheduling process. The AWL planner was developed internally at AWL, because AWL felt that no available software packages could fit their specific needs, e.g. the ability to plan excessive capacity for temporary workers.

Conclusion: AWL has followed the recommendation.

Information and communication structures should be put in place with regard to planning data.
A difference between the period before 2003 and now is that communication lines have been put in place to support the tactical planning activity. For instance, if a project leader needs a substantial increase in hours for an activity or he needs to move a deadline, it has to be reported back to the planner. Another improvement that has been made is the feedback-loop to calculation; department managers have to report the actual number of hours spent on an activity.

Conclusion: AWL has followed the recommendation, although it is difficult to exactly pinpoint whether this was a direct result of Meijerink's report in 2003.

All in all, it seems that the recommendations of Meijerink (2003) have been implemented sparsely. Remarkable is that specifically mathematically more challenging recommendations (incorporating uncertainty and capacity checks/multi-project planning) have not been followed up. An explanation for not following up on these recommendations is the lack of knowledge in the company with regard to complex project planning. Time of employees to deepen into the subject is not available, due to a high workload, often caused by operational issues. Other explanations for not following up on these explanations are that no specific problem holder within AWL has been assigned and there is a lack of support and urgency company-wide. These possible pitfalls for not implementing recommendations uncovered in this section, must be taken into account in the implementation plan in Chapter 5.

2.6 Research Direction

In the remainder of this report, we focus on multi-project planning on the tactical planning level. This section defines the goals for this report.

In terms of the framework by Hans et al. (2007), we focus on the rough-cut capacity planning at AWL. This is the planning of projects on the tactical level. Order acceptance is not explicitly a part of the remainder of this report, however, improved rough-cut capacity planning results in better input for order acceptance decisions.

We focus on algorithms and heuristics to improve the tactical planning at AWL. The input for these algorithms are:

- the earliest starting points and due dates of projects.
- the activities of which projects consist.
- the expected workload of activities.
- the precedence relations of activities.
- the resource groups that are to perform the activities.
- the regular capacity of the resource groups, the cost and maximum level of non-regular capacity per resource group.
- the maximum number of employees that are allowed to work on activities at the same time.

The output of these algorithms is a tactical plan, consisting of:

- multiple project plans.
- start and end dates of activities.
- hours that are to be spent on an activity during a certain week by a certain capacity group.
- capacity graphs, depicting demand over time per resource group.
- estimation of needed non-regular capacity in hours per week.

The algorithms (or heuristics) are judged based on their performance on *KPI 5* (cost of non-regular capacity) and *KPI 6* (extent to which demand is level). This is because the effects of algorithms on these two indicators can be measured directly.

The goals of the remainder of this report are:

- To advise on the applicability of recently developed methods and algorithms for planning, from scientific literature (Chapter 3).
- To show the benefit of the application of algorithms for planning at AWL (Chapter 4).
- To recommend an implementation plan for the new planning method (Chapter 5).

The importance of multi-project planning is illustrated in Section 2.7.

2.7 Importance Of Multi-Project Planning

This section shows what multi-project planning on a tactical level entails and why it is important, by means of some examples. Through the examples, we show the importance of heuristics and smart algorithms. Section 2.7.1 explains by means of an example how we use multi-project planning to improve the tactical plan in terms of some objective. Section 2.7.2 explains by means of an example how to reduce the need for non-regular capacity. Section 2.7.3 discussed robust planning and how this concept can be used to make solid tactical plan. Section 2.7.4 draws conclusions from Chapter 2 by explaining the advantages of multi-project planning using algorithms.

2.7.1 Rationale Behind Multi-Project Planning

This example explains the rationale behind multi-project planning and it gives insight into why multi-project planning at AWL should be done with the help of an algorithm.

The manufacturing facility at AWL is a flexible job shop. Several jobs (or projects) visit work centres (departments), consisting of several machines (or (groups of) workers) following a predetermined route (Pinedo, 2009). According to Pinedo (2009): “Job shops are prevalent in industries where each customer order is unique and has its own parameters”. A setting where each order is unique is an Engineer-to-order (ETO) setting.

A job shop is represented in a directed graph, where nodes depict the activities that need to be performed and arrows represent the order, or the precedence relations of the activities. The start (source; U) and end point (sink; V) are depicted as white nodes. *Figure 9* depicts a fictitious example of such a representation for the jig assembly, consisting of 3 jigs that need to be produced.

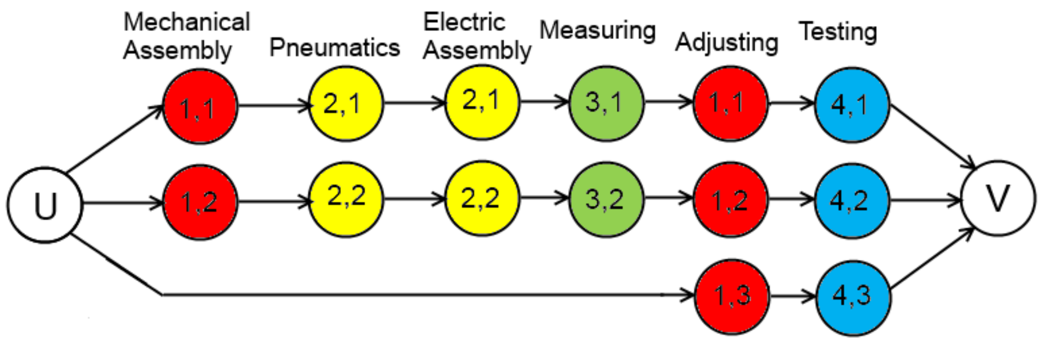


Figure 9: Directed graph for jig assembly

We distinguish four capacity groups: 1. Mechanical assemblers, 2. Electric engineers, 3. Measurers, and 4. PLC-programmers. The first number in the nodes corresponds to the capacity group, the second number corresponds to the jig number. In this example, we assume one worker is available in each capacity group (so 4 workers in total). The numbers in the nodes in *Figure 10* depicts the processing duration of the activities in units of time.

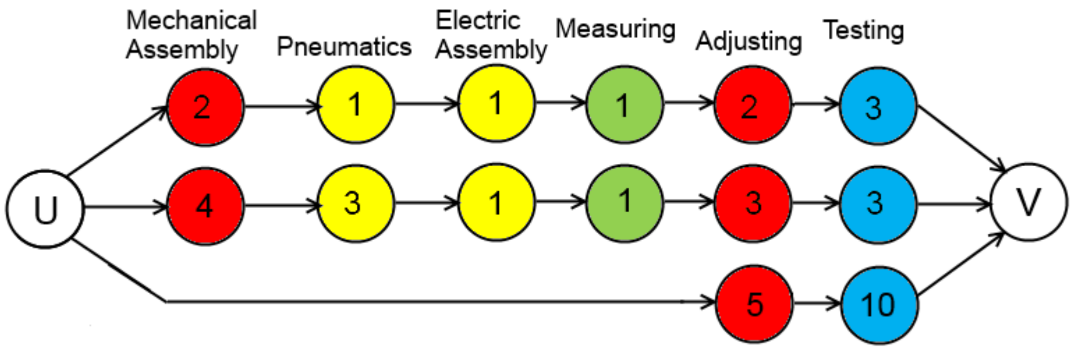


Figure 10: Processing times for jig assembly

We are now concerned with scheduling the order of activities to be performed. We assume the first two jigs (1-2; or the upper two) have already been scheduled (*Figure 11*):

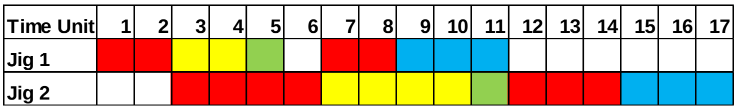


Figure 11: Schedule jig assembly for two jigs

Now jig 3 arrives (at time unit 0), steps 1-4 have already been done in the Czech Republic. If we plan that job against infinite capacity, we would start jig 3 as fast as possible (*Figure 12):*

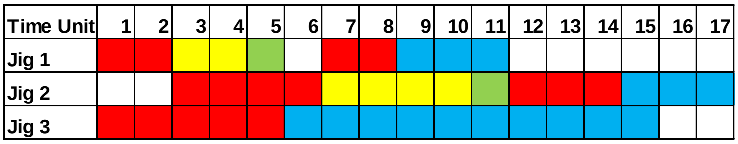


Figure 12: infeasible schedule jig assembly for three jigs

This solution is infeasible, because we need two mechanical assemblers for t=1 to t=5 and 2 plc-programmers for t=9 to t=11 and t=15. At AWL, extra non-regular capacity might be added, but this is not possible in the example. In practice it would also take some time to arrange the non-regular capacity. If we do meet all capacity constraints, without re-scheduling the first two jigs (single-project planning), the earliest possible starting time for jig 3 is t=15 (*Figure 13*):

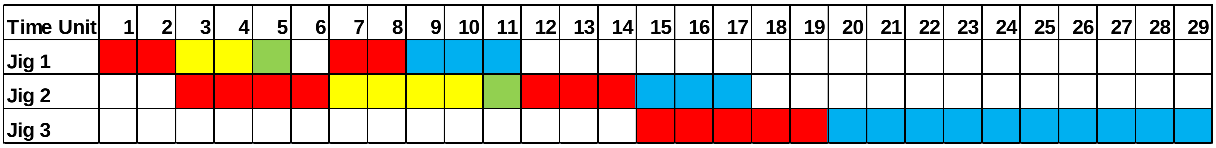


Figure 13: Feasible unfavourable schedule jig assembly for three jigs

Now, when we are allowed to re-schedule (multi-project planning), a few of the possible solutions are (*Figure 14*):

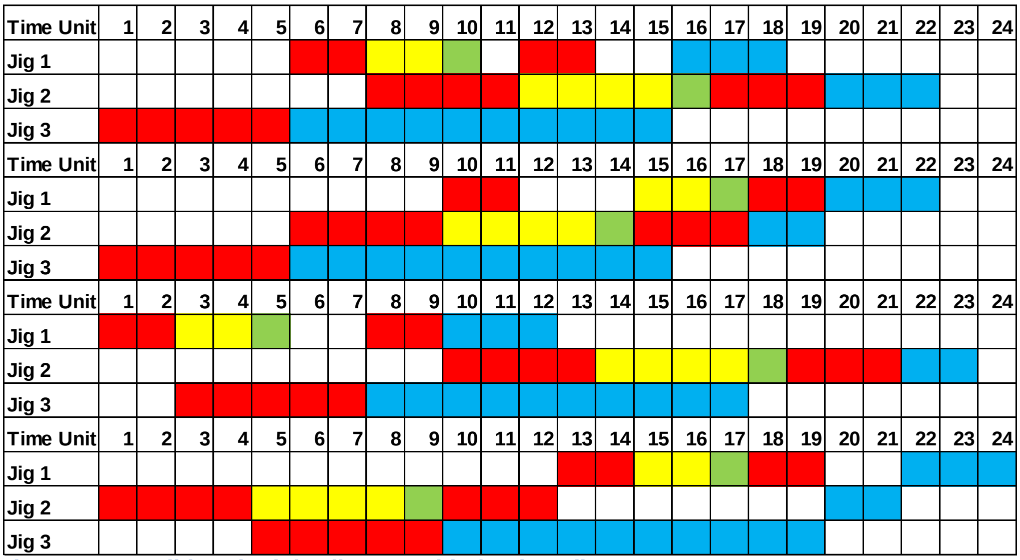


Figure 14: Feasible schedules jig assembly for three jigs

Already, for this simple example, it is quite time consuming to come up with a list of solutions if one manually rearranges the activities. Also, this way, “the best” solution possible is not guaranteed. The question of what is “the best” solution is a separate matter; it could be the schedule with minimum makespan, with minimum average throughput, with minimum total lateness, minimum total costs, the schedule that is most robust to unforeseen events, or it could be a combination. This is a management decision.

2.7.2 Reduction Of Necessary Non-Regular Capacity

In this section, we first plan using a simple forward and then a backward scheduling approach. Then we plan using a simple heuristic, to show that a smart approach reduces the need for non-regular capacity. In this example we simplify the process steps that have to be performed during a project. The process steps as depicted in *Figure 15* are: Engineering, Work Preparation, Assembly, Programming and Testing. In this example, we assume that these steps are done sequentially, so an activity cannot start before all predecessors are finished.

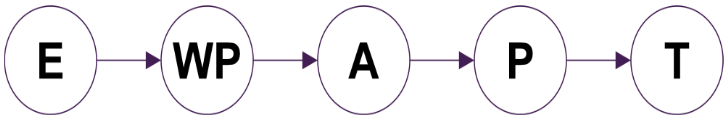


Figure 15: Project process steps

Each step is performed by one capacity group. Each capacity group has a certain fixed number of workers available per week. Engineering has 2 workers, Work Preparation has 4, Assembly has 10, Programming has 3, and Testing has 2. *Table 3* gives four projects that need to be performed and the expected throughput time per activity. This throughput times are realised if a certain number of workers are used, which are given behind the throughput time in brackets. So, for instance, 2 workers are necessary full-time to achieve a throughput time of 1 week for the work preparation activity of project 1. The due dates of the projects are given in the last column of *Table 3*.

	E	WP	A	P	T	Due date
Project 1	2 (1)	1 (2)	6 (6)	4 (1)	1 (1)	Week 15
Project 2	2 (1)	1 (2)	4 (4)	3 (1)	1 (1)	Week 15
Project 3	2 (1)	2 (2)	5 (4)	4 (2)	1 (1)	Week 16
Project 4	-	1 (2)	5 (4)	4 (1)	1 (1)	Week 16

Table 3: Expected workload per project per activity

We now start planning the orders, without looking at fixed capacity constraints and from a single-project perspective. An option is to just plan all activities at their earliest start times (forward scheduling), which we assume is equal to t=0 for all projects. *Figure 16* depicts the results.

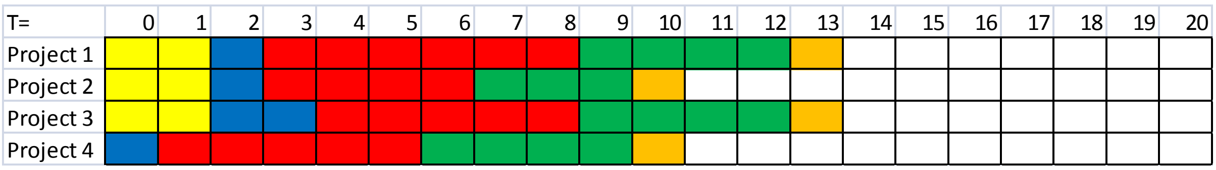


Figure 16: Project plan based on forward scheduling

Another option is to plan activities on their latest possible starting time (backward scheduling), i.e. at the time that such that the projects are finished just-in-time. *Figure 17* depicts the results.

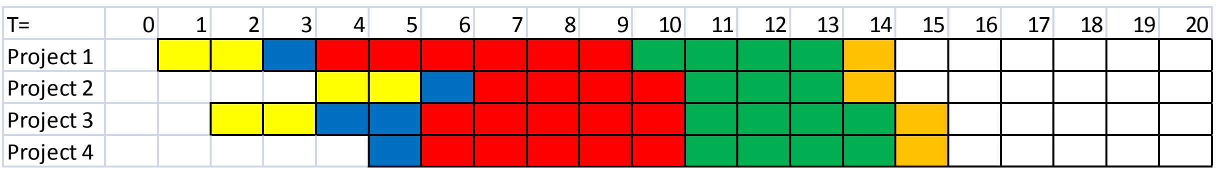


Figure 17: Project plan based on backward scheduling

Both options depicted in *Figure 16* an *Figure 17* come with strongly fluctuating demand, with peak demands leading to a need for non-regular capacity at certain points in time for various capacity groups. For instance, for the plan depicted in *Figure 16, Figure 18* depicts the demand for Engineering and Work Preparation.

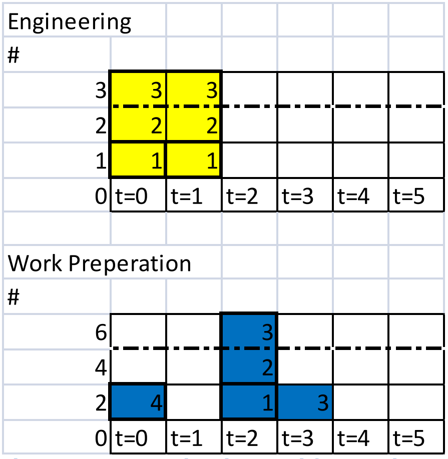


Figure 18: Capacity demand for Engineering and W

Suppose we attempt to spread the workload in *Figure 18* more evenly we might attempt to schedule project 2 to start two time units later. This is feasible, because the expected finishing date of the project will still be before the due date. *Figure 19* depicts the effects of the alteration for the capacity need for Engineering and Work Preparation.

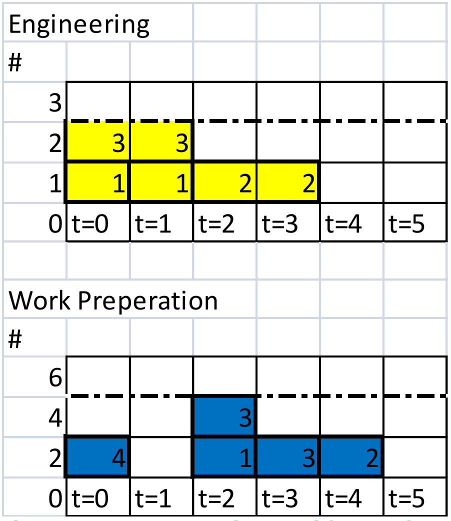


Figure 19: New capacity need for Engineering and Work Preparation

The alteration yields that the engineering department and Work Preparation can cope with demand using only their fixed capacity. However, we have not yet studied the effects of the alteration (delaying project 2 two time units) on other capacity groups. *Figure 20* displays the new capacity need for the programming department.

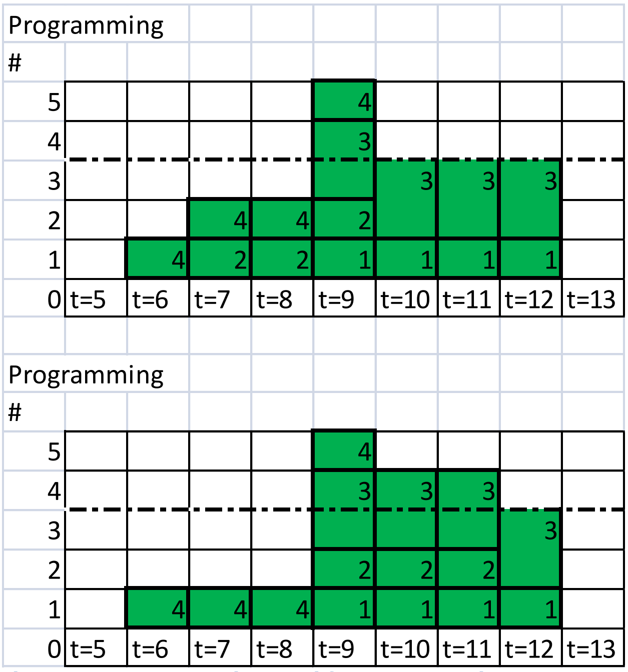


Figure 20: New capacity need for Programming

We see that repairing the plan for capacity groups Engineering and Work Preparation yields that we need to hire one extra programmer for two weeks (t=10 to t=12). We might try to again alter the plan again to decrease the need for non-regular capacity in the programming department. However, the alteration will have an effect on the capacity requirements of other departments. This effect is hard to anticipate, so we would have to recalculate the capacity requirements of other departments. Doing this shifting of jobs to decrease the overall requirements of non-regular capacity by hand is time-consuming and there is no guarantee of an optimal solution, or even a good solution.

An example of a heuristic that reduces the required non-regular capacity in a multi-project rough-cut capacity plan is the Incremental Capacity Planning Algorithm heuristic (ICPA). ICPA can be easily automated, so that a good solution is found within a second by a computer. ICPA is one of the heuristics handled in Chapter 3. *Appendix IV* illustrates how ICPA works for the example described in this section. *Figure 21* displays the resulting schedule.

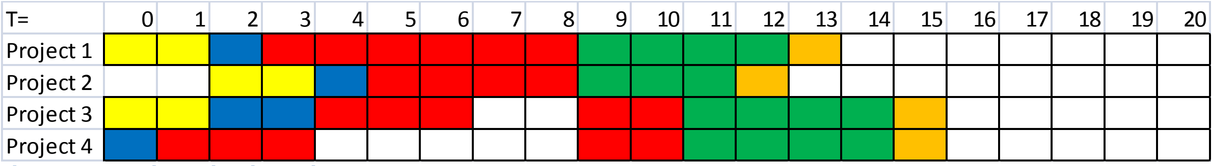


Figure 21: Project plan based on ICPA

Although the project plan in *Figure 21* might look less intuitive than the project plans in *Figure 16* and *Figure 17*, the ICPA project plan performs better in terms of hours of non-regular capacity needed. The plan resulting from the ICPA needs 8*40 hours extra Assembly capacity (*Figure 21*) and 3*40 hours extra Programming capacity. *Table 4* gives the needed non-regular capacity for the other project plans.

	Forward Scheduling	Backward Scheduling	ICPA	Branch & Price (optimal)
Engineering	80	40	0	0
Work Preparation	40	0	0	0
Assembly	960	1200	320	240
Programming	80	240	120	80
Testing	80	80	0	0
Total hours	1240	1560	440	320

Table 4: Comparison of various planning approaches on use of non-regular capacity

We see that employing a simple heuristic reduces the need for non-regular capacity in comparison to forward or backward scheduling. Note that with the reduction of non-regular capacity needed, the fluctuation in demand per department is also reduced. The plan instance is built within a second by an automated ICPA algorithm. More advanced algorithms are available that yield better results, especially for larger problem instances (e.g., more resource groups and more projects).

The branch-and-price algorithm by Hans (2001) solves this example to optimality within three seconds. So, the minimum number of non-regular hours required is 320 hours. *Figure 22* gives the optimal plan in terms of least hours of non-regular capacity needed.

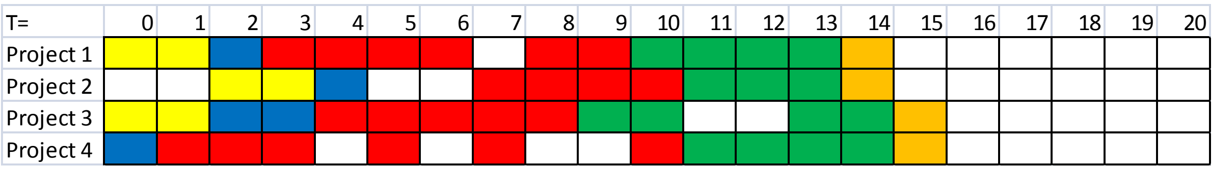


Figure 22: Optimal solution by branch-and-price

The cost of non-regular capacity for various capacity groups can also be incorporated. Furthermore, when an algorithm is automated, the time spent on planning can be reduced.

2.7.3 Robust Planning

This section explains the importance of robust planning. A robust plan is as insensitive to uncertainty as possible.

Wullink et al. (2004) provide an example to illustrate the importance of planning. A resource has a fixed capacity of 40 units per time unit. *Activity 1* needs 60 capacity units on set resource to be processed and *Activity 2* needs an estimated average amount of 10 capacity units. We proceed by planning *Activity 1* for 2 time units (because 60 does not fit on the resource at ones). We choose to equally divide the workload over the two time units. Then we have enough room to plan *Activity 2* at *t=1* (see *Figure 23*).

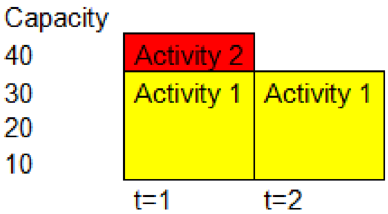


Figure 23: Initial plan for robust planning example

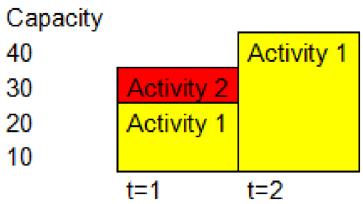


Figure 24: Preferred plan for robust planning example

We have now planned activities optimally in terms of finish dates of the activities and taking into account capacity restrictions. Planning was based on the average expected workload of activities. It is, however, the case that the workload of *Activity 2* is uncertain. An operator estimates that with a chance of 1/3rd the workload is equal to 5, with 1/3rd that workload is 10, and with 1/3rd 15. We now see that the constructed plan in *Figure 23* has a 33.3% chance of exceeding capacity (namely in the case that workload for activity 2 turns out to be 15). If we had taken this uncertainty into account immediately, we would have constructed the plan as depicted in *Figure 24*. The plan in *Figure 24* is equally optimal in terms of the finishing dates of activities as the first plan. However, the second plan has a 0% chance of exceeding capacity. Exceeding capacity would mean extra cost for hiring non-regular capacity or a delayed finishing time of an activity (potentially having an effect on plans or schedules of various resources or various projects). We conclude that taking into account the uncertain duration of an activity when planning has a positive effect on the performance during execution.

2.7.4 Chapter Conclusion

This section concludes Chapter 2 with a discussion of the potential benefits of multi-project planning using algorithms. If we would add to the examples in Section 2.7.1 and Section 2.7.2 more activities, more projects, parallel processes, pre-emption, due-dates, more capacity groups, variable capacity of capacity groups, and heterogeneity within capacity groups, we would come closer to the multi-project situation at AWL. This makes it practically impossible to make a schedule that is close to “the best” solution, without the help of an algorithm and a computer. Such an algorithm has the potential to increase the throughput of projects and level the workload over time for various capacity groups. Furthermore, an algorithm can be used to re-schedule projects periodically, as more information about the projects (tardy deliveries, or other delays) becomes available gradually. Such an algorithm can be used on different hierarchical planning levels, from tactical to operational. If there is insight into how uncertain the estimated workload of an activity is, multi-project planning yields a robust plan.

Another advantage of multi-project planning using algorithms is that it provides insight for Order Acceptance. The order acceptance decision depends on many variables. An aspect is a cost benefit analysis, where the use of non-regular capacity causes a certain proportion of the project cost. The amount of non-regular capacity necessary to reach the goals of a project is related to the due date of the project. For example, if a due date is at a relatively short notice, AWL needs more non-regular capacity to finish a project on time, than when a due date is relatively far away. An algorithm can be used to provide an insight into the relation between the due date of a project and the cost of non-regular capacity needed.

At the order acceptance stage, we do not know the project deadline yet. Rather, the project deadline is a result of tactical planning at the order acceptance stage. The algorithm can plan the project for different prospective feasible due dates. As a result the cost of non-regular capacity given a certain due date is determined. This insight into the effects of a deadline on capacity groups can be used in the order acceptance and negotiation phase of a project. Section 4.5.2 provides insight into how a planning algorithm can be employed to get insight into the effects of an order acceptance decision.

These advantages of multi-project planning using an algorithm, warrant that we investigate the suitable algorithms in the literature. Chapter 3 gives a definition of the mathematical problem that an algorithm needs to solve and we discuss some approaches to solve this problem.

Chapter 3: Literature Review

This chapter consults the scientific literature, with the goal of advising on the applicability of recently developed methods and algorithms from the scientific literature at AWL. Section 3.1 discusses the rough-cut capacity planning problem (RCCP). Section 3.2 discusses methods and algorithms to solve the RCCP.

3.1 Rough-Cut Capacity Planning Problem

This section discusses the rough-cut capacity planning problem (RCCP) and its importance. This section also gives a formal representation of the RCCP. The RCCP is a problem that organisations face in practise at the tactical planning level. RCCP is concerned with the planning of activities (or an aggregation of activities) belonging to projects, taking into account the capacity levels of various capacity groups and the characteristics of the project, such as the due date.

The goal of RCCP is to be able to estimate a due date of the project and to (roughly) estimate the effect of the project on the capacity groups, before a definitive acquisition of the project or in the early stages of a project (Hans et al., 2007). The other two goals of RCCP are to determine milestones and to determine (an estimation of) the needed (non-regular) capacity levels (Hans, 2001).

Often, at the tactical level, not all resources are planned, but an aggregation of resources, which are called manufacturing cells. The capacity groups at AWL can be seen as the manufacturing cells. At AWL, the capacities of these capacity groups are defined by the number of worker hours available. The worker hours available mostly is the bottleneck that defines the capacity, rather than space or available tools. The planning of cells is called the resource loading problem. The detailed planning (operational scheduling) is left to the individual cells.

RCCP is a generalisation of the resource loading problem, where generalised precedence relations are allowed (Hans, 2001). Allowing generalised precedence relations means that activities are not only performed sequentially, but also in parallel. From *Figure 2* (Section 2.1.4) we derive that generalised precedence relations yield that RCCP is a suitable generalisation of the resource loading problem for AWL.

Solving the resource loading problem should result in a plan where the manufacturing cells are not overloaded (Hans, 2001). Even though there is a possibility of arranging non-regular capacity at the operational manufacturing cell level, enough buffer should be maintained for operational schedulers to solve the operational scheduling problem satisfactorily. If the operational scheduling problem cannot be properly solved, then due dates (or milestones) may not be met, or only at high cost of non-regular capacity. The benefits of RCCP are noticed at the operational level in particular. There are two types of RCCP approaches: the resource-driven approach and the time-driven approach (De Boer, 1998).

The resource-driven approach assumes that capacity is fixed, due dates are soft, and the objective is to minimise lateness or tardiness. So, the goal of the resource-driven approach to RCCP is to plan all activities such that they fit within the capacity constraints and to then minimise the sum of the tardiness or lateness of projects. Tardiness is defined as by how much time a job is finished after the due date. Lateness is similar to tardiness, with the difference that lateness can have a negative value. For instance, if a job is finished 2 time units before the due date, then lateness =-2 and tardiness =0. If a job is finished 2 time units after the due date, then both lateness and tardiness are equal to 2.

The time-driven RCCP approach assumes that capacity is a soft restriction, due dates are a fixed hard restriction, and the objective is to minimise the use of non-regular capacity. So, the time-driven approach to RCCP aims to minimise the (cost of) non-regular capacity used over all capacity groups, such that the customer deadlines are met. Based on two observations from Chapter 2, the time-driven RCCP approach is more suitable for AWL. The first observation: deadlines of projects are very important for AWL's customers. The second observation: non-regular capacity can be arranged for most capacity groups within AWL, at a fairly short notice. So at the tactical planning stage, non-regular capacity can still be arranged for most capacity groups, but deadlines are fixed (after the acquisition of the project).

We provide a formal description of the time-driven RCCP, based on the formulation by De Boer (1998). N activities $A_1, \ldots, A_N$, which are part of projects, need to be planned on K resources $R_1, \ldots, R_K$. The time horizon is divided in T time-buckets $t = 1, \ldots, T$. Each resource R_k has Q_{kt} capacity available in time-bucket t. Activity A_a requires q_{ak} hours of processing time on resource R_k. In any time-bucket at most $1/p_a$ of an activity A_a can be executed, thus p_a is the minimum duration of activity A_a. Activity A_a's release date is r_a and its deadline is d_a. So, activity A_a cannot be processed before time-bucket r_a and after time-bucket d_a (time-bucket d_a+1 and later time-buckets).

x_{at} indicates the proportion of the workload of activity A_a performed in time-bucket t. The set P_a contains the direct predecessors of activity A_a, so each activity in P_a must be finished before A_a can start.

A plan specifies when what proportion of activities is performed. A plan is feasible if:

1: All work of each activity is performed within an allowed time window:

$$\sum_{t=r_a}^{d_a} x_{at} = 1, \quad \forall a$$

2: In each time-bucket, no more then $1/p_a$ of an activity is performed:

$$x_{at} \leq \frac{1}{p_a}, \quad t = r_a, \ldots, d_a; \forall a$$

3: Precedence relations are adhered to:

$$x_{at} = 0 \; if \sum_{t=r_b}^{t-1} x_{bt} < 1, \quad t = r_a, \ldots, d_a;\; A_b \in P_a; \forall a$$

4: All variables are non-negative:

$$x_{at} \geq 0, \quad t = r_a, \ldots, d_a; \forall a$$

5: Activities do not start before the release date or end after the deadline:

$$x_{at} = 0, \quad t = 1, \ldots., r_a - 1, d_a + 1, \ldots, T; \forall a$$

The objective is to find a feasible plan in which the non-regular capacity is minimised (*KPI 5* in Chapter 2):

$$1\text{: minimise} \sum_{t=1}^{T} \sum_{k=1}^{K} max \left\{ 0, \sum_{a=1}^{N} q_{ak} x_{at} - Q_{kt} \right\}$$

An alternative objective function is to minimise the deviation of needed capacity for a capacity group during a time-bucket from the average needed capacity of the capacity group during the considered time span (*KPI 6* in Chapter 2):

$$2: \text{minimise} \sum_{k=1}^{K} \sum_{t=1}^{T} \left| \left(\sum_{a=1}^{N} q_{ak} x_{at} \right) - \frac{\sum_{t=1}^{T} \sum_{a=1}^{N} q_{ak} x_{at}}{T} \right|$$

The formulation of the RCCP can be augmented with cost of non-regular capacity for various capacity groups and with a limit to non-regular capacity for various capacity groups. We denote the cost of using one hour of non-regular capacity for capacity group *k* in time-bucket *t* by c_{kt}. Now, we translate the objective of minimising non-regular hours to an objective of minimising costs.

$$3: \text{minimise} \sum_{t=1}^{T} \sum_{k=1}^{K} max \left\{ 0, \left(\sum_{a=1}^{N} q_{ak} x_{at} - Q_{kt} \right) c_{kt} \right\}$$

Q^*_{kt} denotes the limit to non-regular capacity available for resource *k* in time-bucket *t*. The usage of limits to non-regular capacity implies the following extra restrictions to the problem formulation.

6: Regular plus non-regular capacity should not be exceeded:

$$\sum_{a=1}^{N} q_{ak} x_{at} \leq Q^*_{kt} + Q_{kt} \qquad \forall k, t$$

If an algorithm for the AWL tactical planning function takes the maximum possible non-regular capacity of capacity groups into account, it means for some problem instances that the project deadline restriction cannot be completely hard. Capacity restrictions combined with the deadline restrictions may lead to a situation where the problem instance cannot be fitted. We solve this by the addition of a component to the objective function that gives a high penalty for unmet deadlines. *M* denotes either a big number or an estimation of the actual total cost of not meeting a deadline by one time unit. $\sum_{k=1}^{K} \sum_{a=1}^{N} \sum_{t=d_a+1}^{T} q_{ak} x_{at}$ denotes the total tardiness of projects, so any of the proposed objective functions can by augmented with "$+M \sum_{k=1}^{K} \sum_{a=1}^{N} \sum_{t=d_a+1}^{T} q_{ak} x_{at}$".

Since unmet deadlines are now allowed (but restrained by the objective function), we alter *Restriction 5* and *Restriction 1* to:

1*: All work of each activity is performed after the release date:

$$\sum_{t=r_a}^{\mathrm{T}} x_{at} = 1, \quad \forall a$$

5*: Activities do not start before the release date:

$$x_{at} = 0, \quad t = 1, \ldots, r_a - 1; \forall a$$

The following sections discuss different approaches that are used to tackle the RCCP. The performance of these heuristics and algorithms are judged based on *KPI 5* (cost of non-regular capacity) and *KPI 6* (extent to which demand is level).

3.2 Methods & Algorithms For RCCP

This section defines appropriate recently developed methods and algorithms found in the scientific literature. This section focuses on approaches which solve the RCCP as described in Section 3.1. Relatively little work has been published in literature that is dedicated to the (time-driven) RCCP. While, for instance, a lot of work has been dedicated to the operational counterpart of the RCCP, the RCPSP, for instance by Guldemond et al. (2008). Cherkaoui et al. (2013) present a literature review on RCCP heuristics and algorithms. Section 3.2.1 discusses a relatively simple heuristic: the ICPA (incremental capacity planning algorithm). Section 3.2.2

describes LP-based heuristics for the RCCP. Section 3.2.3 discusses the branch-and-price algorithm, which is able to solve a planning problem formulated as an RCCP to optimality. The last two sections discuss two approaches based on the branch-and-price algorithm that incorporate uncertainty. Section 3.2.4 discusses a scenario-based approach and Section 3.2.5 discusses a so-called fuzzy approach to the RCCP.

3.2.1 ICPA Heuristic

This section briefly explains the working of the ICPA (incremental capacity planning algorithm) heuristic and discusses the advantages and disadvantages of the heuristic. The word heuristic means that the method does not guarantee an optimal solution, but the computation times of heuristics are usually shorter than those of exact methods. This heuristic is a constructive heuristic; it does not need an initial solution to work from.

The ICPA sorts the activities based on their due date and starts planning the jobs with the earliest due date. Here, the due date of the activity is the latest possible finishing time of the activity, such that the project deadline can still be met. Based on available capacity of resources, the minimum duration of an activity, and the part of the activity already planned, the algorithm plans activities as early as possible. In the time-driven variant of the ICPA heuristic, which is most suitable for AWL, the capacity of resources needs to be “increased” to make the activities fit on the resources and make sure they are finished on time. In an AWL setting, the increase of the capacity means that flexible capacity should be arranged. *Figure 25* on the next page schematically depicts the working of the ICPA heuristic. De Boer (1998) describes the working of the ICPA heuristic in detail and *Appendix IV* gives an example.

The heuristic copes with the problem that there is a limit to the number of workers working efficiently on one activity at the same time. For instance, if first you have one assembler assembling a jig, and then eight assemblers assembling a jig, it does not mean that the activity is performed eight times as fast, because the jig is not big enough to work on with eight assemblers. An assumption of the ICPA heuristic is that a job has a minimum processing time.

There are two disadvantages of the standard ICPA related to the tactical planning problem considered at AWL. First, ICPA tries to minimise hours of non-regular capacity used, whereas the cost of non-regular capacity used is more relevant. ICPA constructs plans in a way that demand for non-regular capacity is generally higher for capacity groups in a later stage of the project. The second disadvantage, is that ICPA assumes that for all capacity groups an infinite amount of non-regular capacity can be added. The assumption of infinite non-regular capacity is not realistic in the AWL setting. In Section 4.1, we propose an extension of the ICPA that can cope with a non-regular capacity limit.

As a conclusion of this section, the advantages and disadvantages of the ICPA are listed:

Advantages:
- Fast plan construction.
- Variable processing time of activities.

Disadvantages:
- No guarantee of an optimal solution.
- Assumes infinite non-regular capacity possibility.
- Minimises non-regular hours instead of costs.

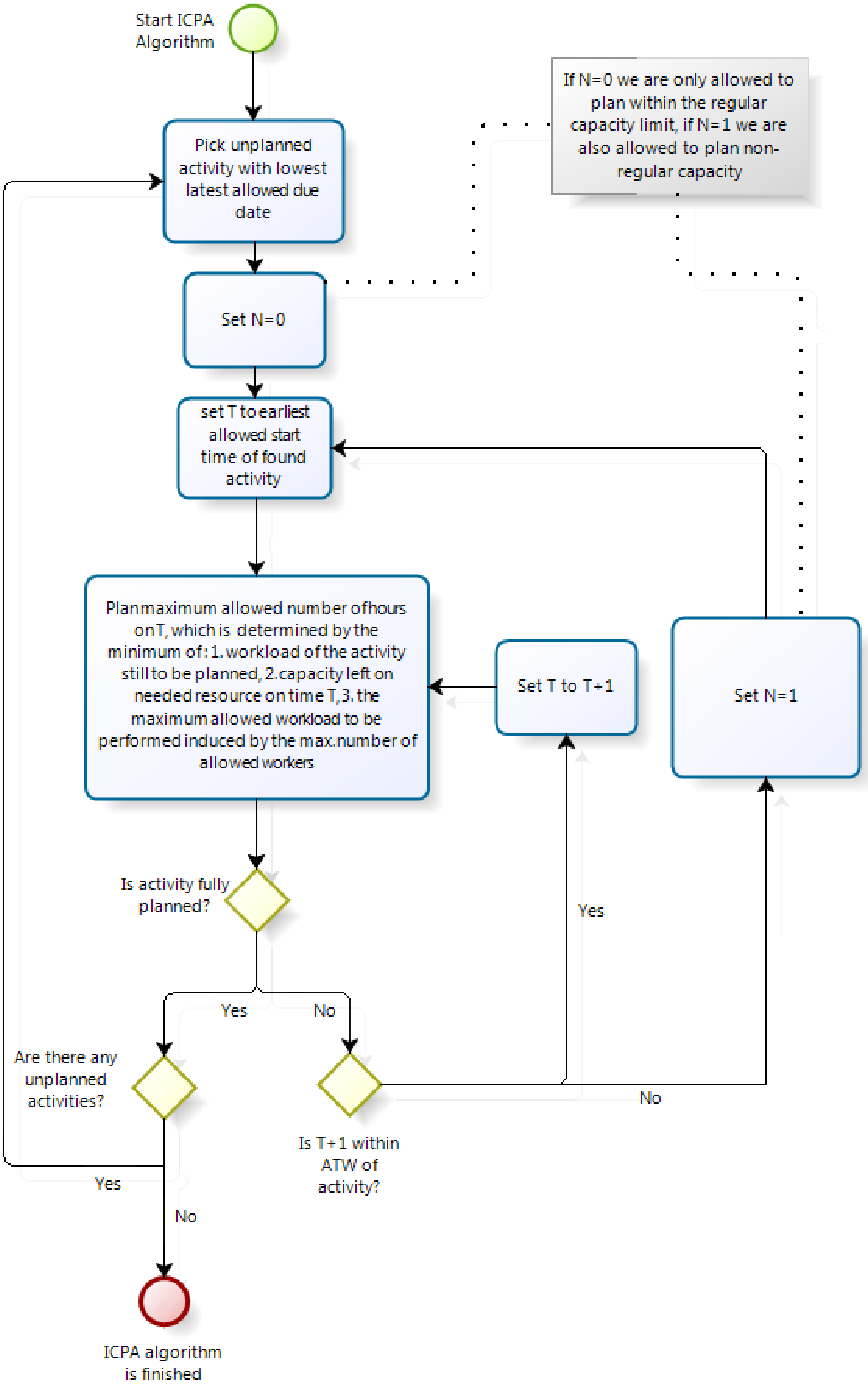


Figure 25: ICPA heuristic

3.2.2 LP-Based Heuristics

This section discusses several LP-based heuristics for the RCCP. De Boer (1998) and Gademann & Schutten (2005) give examples of approaches to multi-project planning that employ linear programming. A planning problem can be formulated as a maximisation or minimisation problem, that is bound by a set of constraints. These constraints limit the allowed value of certain variables. If a problem can be formulated as a LP problem, then a computer can calculate an optimal solution in terms of the objective function.

Gademann & Schutten (2005) propose several LP-based heuristics using so-called available-to-work windows. Available-to-work windows are binary variables that state whether a certain activity is allowed to be processed at a certain time. Gademann & Schutten (2005) distinguish three types of solution approaches:

- **Category 1:** constructive heuristics
- **Category 2:** heuristics that start with infeasible solutions and convert these to feasible solutions
- **Category 3:** heuristics that improve feasible solutions

An example of a category 1 heuristic is ICPA. ICPA constructs a feasible plan from scratch.
Of the many LP-based heuristics proposed for the RCCP, the so-called heuristics H_{feas} (category 2) and H_{enum} (category 3) clearly outperform the other heuristics (Gademann & Schutten, 2005).

H_{feas} starts from a feasible solution that is derived from a constructive method, such as ICPA. Then the ATW windows are iteratively altered in a search algorithm based on information about the dual values of changing the ATW window of an activity. For each job there are four ways to alter the ATW by one time unit, namely by increasing or decreasing the allowed starting or end time by one time unit. For each possible alteration of the time windows in a project the effect is estimated by looking at dual values of the ATW constraint. Next, the LPs for the neighbour solutions that result from one alteration are solved in order of largest expected benefit to the objective function. The first neighbour that actually decreases the objective function is picked and from this solution the search algorithm starts again, until no more improvement is found. The search method adopted is a simple local search algorithm. It considers only direct neighbour solutions that improve the objective function.

H_{enum} is a heuristic that starts from an infeasible solution found by solving an LP in which precedence relations are not taken into account. Each iteration repairs a broken precedence relation. The next precedence relation to be repaired is the precedence relation with the least "slack" . Here, slack is defined as the difference between the start date of the first activity and the finish date of the second activity, minus the processing times of both activities. The precedence relation is repaired by defining a time *T* before which the first job in the precedence relation needs to be finished and after which the second job is allowed to start. *T* is defined by looking at the effects of all values of *T* on the objective function and choosing the most favourable value. H_{enum} proceeds until all precedence relations have been fixed.

Advantages:

- Based on work content (workload) of activities.
- Objective is to minimise costs of non-regular capacity.

Disadvantages:

- No optimal solution guarantee.
- LP-solver necessary.
- Assumes infinite non-regular capacity possibility.

3.2.3 Branch-And-Price Algorithm

This section discusses the branch-and-price algorithm by Hans (2001). The branch-and-price algorithm is partially based on the branch-and-bound method. The branch-and-bound method is a systematic way, using partitioning, to tackle a mathematical problem that can be formulated as an ILP. The problem considered can be seen as a branching tree. At the root node of the tree is the original problem, consisting of a solution space with all feasible solutions to the problem. Branching adds a constraint to the problem, creating child nodes. Multiple constraint values are investigated. This way, the problem is partitioned into smaller problems. The branching process is continued from the child nodes. In a minimisation problem, such as the planning problem considered in this report, a node is not considered further (fathomed), if the lower bound of the node is higher than the objective value of the currently best found solution (incumbent solution). The lower bound of a node is an approximation of the lowest the objective value of the node can become if we branch further. This lower bound is determined by Lagrangian relaxation. Nodes are fathomed (or pruned) when the problem in a node is infeasible.

Branch-and-price involves column generation. Columns are all possible combinations of allowed starting and end times of activities in projects. The algorithm starts by first solving the so-called restricted master problem, which is a relaxation of an instance of the problem were many columns are left out. A pricing algorithm is used to verify optimality. The pricing problem determines which columns have to be added. If the pricing algorithm determines that the current solution is not optimal, i.e. there are still columns with negative reduced costs, then a column is added for the column with negative reduced costs. When the optimal solution of the relaxation problem (restricted master problem) is found, the solution is usually fractional (some variables are not integer). Branching is performed to find a feasible integer solution to the ILP. The column pool is partitioned. When all nodes are explored, the incumbent solution is the optimal solution for the ILP. *Figure 26* displays a schematic depiction of the branch-and-price algorithm.

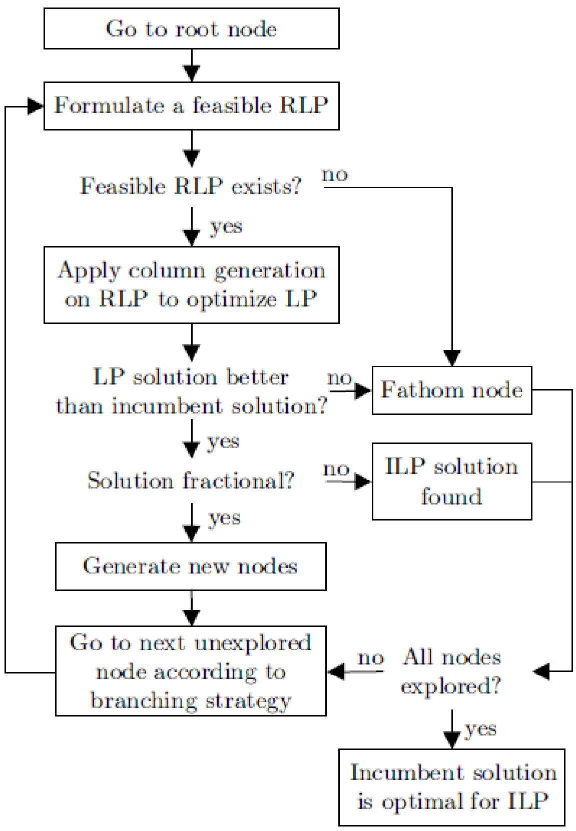


Figure 26: Branch-and-price algorithm (Hans, 2001)

Advantages:

- Optimal solution.
- Based on work content (workload) of activities.
- Objective is to minimise costs of non-regular capacity.
- Maximum non-regular capacity is taken into account.

Disadvantages:

- High computation time (especially for large problem instances).
- Uncertainty is not taken into account.
- LP-solver necessary.
- Assumes infinite non-regular capacity possibility.

3.2.4 Scenario-Based Approach For Flexible Resource Loading Under Uncertainty

This section discusses a scenario-based approach for flexible resource loading under uncertainty proposed by Wullink et al. (2004). The approach is based on an MILP (mixed integer linear programming problem) to find a plan with minimum expected costs over all scenarios. By a branch-and-bound algorithm, the problem at hand can be solved to optimality. The approach is an extension of the approach by Hans (2001), he proposed a deterministic approach (not incorporating uncertainty). The objective of the approach by Wullink et al. (2004) is to plan the orders so that capacity groups are used as efficiently as possible, customer due dates are met, and the resulting plan is robust (as insensitive to uncertainty as possible).

A multi-mode approach is used to account for uncertainty. A mode is a scenario on the individual activity level, with each mode a different workload is associated. For example, the planner could take into account that with some probability rework has to be performed for an activity. With a simple example, Wullink et al. (2004) explain the importance of taking into account the uncertainty of an activity's duration and how this can be done. If uncertainty is taken into account in a plan, this is called robust planning, i.e. planning in such a way that a plan is the least susceptive for (unexpected) delays. Computational results show that their approach, when taking into account uncertainty, outperforms deterministic approaches (Wullink et al., 2004).

Advantages:

- Optimal solution.
- Based on work content (workload) of activities.
- Multiple modes (uncertainty is taken into account).
- Objective is to minimise costs of non-regular capacity.
- Assumes finite non-regular capacity possibility.

Disadvantages:

- High computation time (especially for large problem instances).
- Modes of activities have to be defined (which might be difficult due to limited information and time-consuming).
- LP-solver necessary.

3.2.5 Fuzzy Approach

This section discusses a fuzzy approach to the RCCP proposed by Masmoudi et al. (2011). Uncertainty of activity durations is modelled by a fuzzy function. Masmoudi et al. (2011) also propose a simulated annealing based meta-heuristic to solve the RCCP. Two different objectives are distinguished: minimisation of costs and maximisation of robustness. Where robustness is defined as the probability of exceeding a capacity limit. Overtime, subcontracting, and the possibility of hiring temporary workers are separately incorporated in the model.

Contrary to the scenario-based approach described in Section 3.2.4, uncertainty is modelled with continuous distributions using fuzzy modelling. Masmoudi et al. (2011) give an example of how such a fuzzy function should be derived. For instance, an operator responsible for estimating the workload of a task states it probably takes 100 to 140 hours, but in extreme cases it might take 80 to 160 hours. Then the workload of an activity is given by a four point representation [80, 100, 140, 160], from which a continuous function with a trapezoidal profile is derived.

The approach starts by the initialisation of a solution with a feasible set of ATW windows. Then an activity is chosen by looking at the activity that has the highest slack in the time period with the highest minimum expected workload (an activity can also be chosen randomly). Then, a certain fraction of the workload of this activity allocated to the considered time unit is evenly re-divided over the other time units in which the activity is allowed to be processed. Next, an activity with minimum slack is chosen (an activity can also be chosen randomly). For this activity either start or completion times are either increased or decreased by 1.

Advantages:

- Based on work content (workload) of activities.
- Objective is to minimise costs of non-regular capacity or to maximise robustness.
- Activity workload as a function (uncertainty is taken into account).
- Assumes finite non-regular capacity possibility.

Disadvantages:

- Likelihoods of activity workloads have to be estimated (which might be time-consuming and difficult due to limited information).

Chapter 4 applies some of the algorithms described in this section to an AWL-based problem instance. We did not apply all algorithms described. The Scenario-Based approach and the Fuzzy approach are unsuitable, because AWL has no information about the uncertainty of activity workload estimations. The intention was to include the branch-and-price algorithm in the analyses, however, because of technical difficulties and time-constraints, we were unable to do this.

Chapter 4: Experiments

This chapter discusses the design of the experiments to show the performance of some of the algorithms proposed in Chapter 3. We also compare the algorithms to the current method of planning. Section 4.1 describes the algorithms employed in the experiment and how we compare resulting tactical plans. Section 4.2 describes the base problem instance. Section 4.3 describes the assumptions that are necessary to provide the right input for the algorithms and to make a fair comparison of the algorithms to the current situation. Section 4.4 shows the basic results from the experiment. Section 4.5 describes several sensitivity analyses. Section 4.6 gives a further discussion of the results from Section 4.4 and Section 4.5. The goal of the experiments is to show how AWL can employ algorithms for tactical planning and what the benefits are.

4.1 Algorithms Employed

This section describes the considered alternatives and on which KPIs they are compared. The observed approaches are:

- Current planning method
- LP-based heuristic H_{feas} (Gademann & Schutten, 2005)
- ICPA (De Boer, 1998)
- Augmented ICPA

The LP-Heuristic (H_{feas}) and the ICPA are the approaches discussed in Chapter 3, that we were able to employ during this research. Of the LP-based heuristics described by Gademann & Schutten (2005), we use H_{feas}. In the remainder of this report we refer to H_{feas} as the LP-Heuristic. We choose to use H_{feas}, because this is one of the two best performing LP-based heuristics from the article by Gademann & Schutten (2005) and a software package that employs this algorithm is available.

Augmented ICPA is the ICPA as described in Chapter 3 augmented with the ability to incorporate non-regular capacity restrictions. This means that a maximum level of non-regular capacity can be set per capacity group and the algorithm does not exceed this maximum. During the planning of activities, we propose to track the slack of the planned activities and the order in which activities are planned. We define slack as the actual duration minus the minimum allowed duration.

When during the algorithm, we come across an activity that does not fit within regular plus non-regular capacity, we go back a few activities in the algorithm. We go back to the activity in the same project as the activity that doesn't fit with the highest slack and un-plan all activities that have been planned after that activity. When several activities with the same amount of slack exist in a project, we pick out of that set the activity that was planned last. Then, for set activity earlier in the project chain, we set back the latest allowed finish time of the activity back to the planned finish time minus one time unit. We re-plan that activity to fit its new ATW and continue the ICPA algorithm. When we encounter an activity (that does not fit within regular and non-regular capacity) with no predecessor in the project with slack, we look at activities that have already been planned for other projects. We choose to decrease the latest allowed finish time of the activity with the highest slack by one. All activities that had been planned after that activity (and the activity itself) are unplanned and ICPA recommences with the adapted time window.

Appendix VII describes two examples that explain the working of the ICPA algorithm. The second example, also proves that Augmented ICPA does not always find a solution to the tactical planning problem, even though a valid solution exists. *Figure 27* displays the steps with which ICPA is augmented to make it suitable for maximum non-regular capacity restrictions of capacity groups.

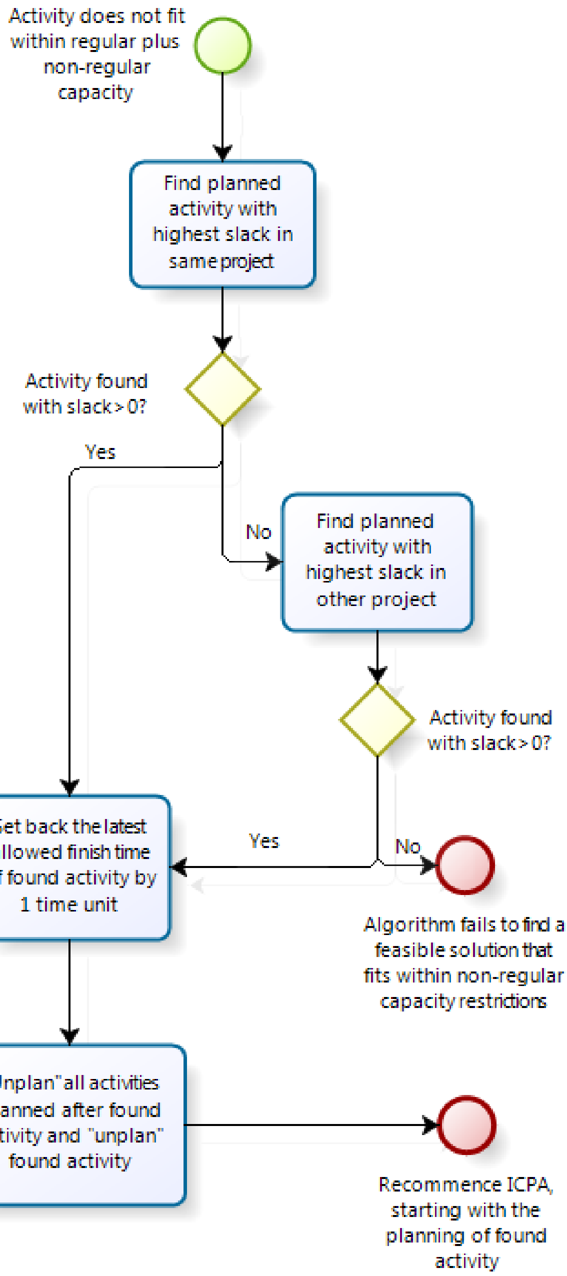


Figure 27: Augmented ICPA (extra steps)

The approaches are compared on the following KPIs:

- **KPI 5:** the cost of non-regular capacity needed.
- **KPI 6:** fluctuation of capacity demand.
- **KPI 10:** time needed to create a plan.

Recall that the goal reflected in *KPI 6* is to level demand of capacity. This renders that if non-regular capacity is used, temporary workers are hired for a longer consecutive period. This KPI is measured by two different measures. The first measure (Fluctuation Coefficient I) is the sum over all resources and weeks of the square roots of the average deviations of needed capacity from the average capacity demands. The second measure (Fluctuation Coefficient II) for *KPI 6* is the sum over all resources and weeks of the square roots of the deviations for a week's capacity demand from the preceding week's capacity demand.

We do not assess other KPIs defined in Section 2.3 because they are influenced by other influences than the tactical plan. Furthermore, these other KPIs cannot be measured at the tactical planning stage, but only at the operational level. For instance, the extent to which milestones are met can only be measured at the operational stage, after the execution of a plan. Measuring these other KPIs would imply a costly and time consuming experimental setting in which developed plans are completely executed and a new planning system is already implemented.

4.2 Base Problem Instance

This section describes the problem instance used for the comparison. A problem instance is the set of data on which a planning method is employed to build a tactical plan. A problem instance consists of the following data (for some time horizon):

- the earliest release and due dates of projects.
- the project activities.
- the expected workload of activities.
- the precedence relations between activities.
- the resource groups that are to perform the activities.
- the regular capacity profile of the resource groups, the cost and maximum level of non-regular capacity per resource group.
- the maximum number of employees that are allowed to work on activities at the same time, per activity.

We were not able to retrieve this data directly from the current planning system at AWL. Currently, the data from AWL's systems, is often incomplete, polluted, and/or ambiguous. Section 5.1 elaborates on the reasons why this was not possible in a reasonable amount of time and what needs to be done in order to couple the current planning system with the planning algorithms described. We retrieved data directly from the tactical plans of 18 projects (MS project files) and manually typed the data into the Delphi application for the ICPA algorithm. The data was retrieved in week 35 of 2013 and entails the planning horizon of week 36 in 2013 to week 20 in 2014 (the latest due date of the considered projects).

We retrieved release and due dates of projects, expected workloads of activities, the resource groups that perform the activities and the current start and end dates of activities directly from the tactical plans. Information about the regular capacity of capacity groups comes from an Excel-file derived from AWL's ERP-system. The cost of one hour of non-regular capacity per capacity group is an estimation of department managers. The assumption is that the maximum level of non-regular capacity for each capacity group is infinite, because boundaries estimated by department managers are already exceeded by the current tactical plan.

For the current planning method, we assume that the workload of the activity is equally divided over the planning interval of the activity. For activities that have already commenced before week 36, we assume that the workload that still needs to be done is proportional to the part of the interval that is still to come. The maximum number of employees that are allowed to work on activities at the same time, per activity, was calculated according to the assumption that Section 4.3 describes.

Figure 28 depicts the general breakdown structure of an AWL project. A project consists of one or more machines to be built. These machines might consist of one or more

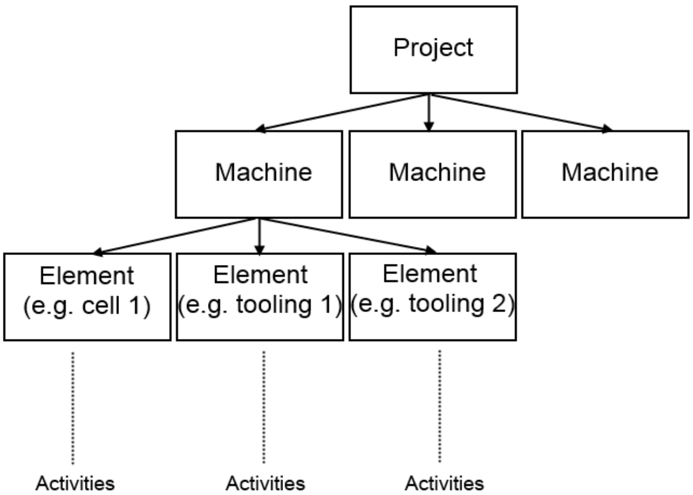


Figure 28: General breakdown structure of an AWL project

elements, which might in turn consist of several sub-elements. We simplified the considered projects in the problem instance a bit, by only looking at machine-level. So for each machine and each activity type, the workload of activities is accumulated into one activity. For instance, in *Figure 28*, the activities belonging to the elements of the same type (e.g., tooling 1 and tooling 2), are merged into one activity for the whole machine. So, the workloads of the two original activities are summed. In the original tactical plans activities of the same type, of the same machine, of different elements, are planned completely in parallel, so the same start and end dates.

From now on, in this report, we refer to this problem instance as the base problem instance. In Section 4.5, we study problem instances that we derive from the base problem instance.

Appendix V describes the various prototype software applications that we use in this research. The performance of the current situation and the ICPA algorithm is measured in Application II, the performance of the LP-base heuristic is measured in Application III. Application II includes a functionality for the translation of the data in such a manner that it can be used as input for Application III. All tests were performed on a Pentium(R) Dual-Core CPU T4200 @ 2.00 GHz.

4.3 Assumptions

This section discusses assumptions to which we adhere in the experiments, in order to be able to compare the algorithms to the current tactical plan in a fair manner.

Maximum number of workers per activity

Since we do not know the maximum workers that are allowed to work on an activity at the same time, we aim to approximate reality by assuming that the maximum number of workers assigned to an activity in the current tactical plan is the maximum number of workers allowed to work on this activity at the same time. The maximum proportion of the workload of an activity that is assigned to a time-slot, divided by forty (hours of an FTE), and rounded up to the nearest integer, defines the maximum allowed number of workers. The assumption made with regard to the maximum number of workers limits our solution space, if the actual allowed workers at the same time is higher for some activity, resulting plans might improve.

Minimum activity durations in the process optimisation- and the external phase

The process optimisation phase and the external phase are the final two phases in each project, consisting of several activities. The durations of activities in the process optimisation phase and the external phase are determined somewhat differently than durations of other activities. Because of the uncertainty and the iterative nature of these activities, it is unrealistic to determine the minimum duration of these activities by simply dividing the workload by the number of FTEs that can work on the activity at the same time (FTE*40). For instance, although it seems that 4 weeks is a long duration for these activities, since the estimated workload in hours is fairly low, management sees it as necessary to plan a duration of the activity of several weeks.

In order to be able to compare the algorithms to the current tactical planning in a fair manner, we restrict the algorithms by saying that the minimum duration of activities in the optimisation phase and the external phase are equal to the duration of the activities as they are in the current planning. Also, the parts production and purchase activity always has a minimum duration of six weeks. The six weeks minimum duration is a rule within AWL and is the time in which procurement can purchase parts and get them delivered.

Limit to 18 projects

Since there are currently 80 active projects at AWL, and since it is not feasible to automatically retrieve data from the AWL planning system (such as described in Section 5.1), we limit the number of projects considered. The reason for this is that manually copying relevant data from all project plans is too time consuming. We limit the number of projects to the 18 projects that have the most effect on the assembly department. We assume that we cannot re-plan the other projects (projects needing capacity of other departments, but not assembly). Therefore we determine the regular capacity of capacity groups per time unit by the actual regular capacity per time unit minus the capacity taken by projects other than the 18 projects considered per time unit.

4.4 Results

This section shows the results from the experiment on the base problem instance. Table 5 compares four solution approaches: ICPA, Augmented ICPA, the LP-heuristic with an objective of minimising hours of non-regular time used, and the LP-Heuristic with an objective of minimising the cost of non-regular hours used. The second column of the table show the time it takes the various approaches to find a solution, the third column shows the number of non-regular hours needed for the plan, the fourth column shows the associated costs, and the last two columns show the two fluctuation measures described in Section 4.1.

	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
Current Plan	X	32.138	1.618.158	7.493	2.004
ICPA	<1	17.783	882.960	7.465	2.431
Aug. ICPA	<1	X	X	X	X
LP Heuristic (obj.: min. hours)	108	17.143	847.195	4.552	3.070
LP Heuristic (obj.: min. costs)	38	17.847	880.501	4.625	3.117

Table 5: Performance of several approaches

Table 5 distinguishes between performance measurements of ICPA and Augmented ICPA. The basic ICPA does not take into account non-regular capacity restrictions, whereas Augmented ICPA takes into account the non-regular capacity restrictions as described in *Appendix I*. The current tactical plan exceeds the non-regular capacity restrictions on several points. Therefore, in order to make a fair comparison, it is not necessary that an algorithm stays within these boundaries per se. Employing Augmented ICPA shows that the algorithm is not able to determine a feasible solution for this problem instance, so staying within the non-regular capacity boundaries.

Remarkable, is that the LP-Heuristic with an objective of minimising costs did not find a plan with lower cost than the LP-Heuristic with an objective of minimising the non-regular hours. In most subsequent experiments we see, however, that the LP-Heuristic with an objective of minimising costs does find a plan with lower cost than the LP-Heuristic with an objective of minimising the non-regular hours. Finding lower cost with the cost objective is, however, not a certainty. This is due to the nature of the local search algorithm that might get stuck in local optima. It is possible that, sub sequentially altering ATW's according to an expected decrease in hours needed, results in a plan with lower cost than when ATW's are sub sequentially altered according to an expected decrease in costs. Section 4.6.3 discusses the varying performance of the LP-Heuristic.

The results show that all heuristics substantially improve on the current tactical plan, in terms of the non-regular hours needed and the cost associated with these hours. The percentage by which the costs are reduced when we compare the LP-Heuristic to the current tactical plan is 45% percent. We have some remarks and perspectives on this result in Section 4.6. For the basic problem instance, we see that the LP-Heuristic, with the objective of minimising the non-regular hours, improves on the ICPA solution with 4.2% for the cost objective and with 3.7% for the hours objective. Since we only have the base problem instance, we cannot yet state if these percentages are representative for other problem instances. We get a better view of the relative performances of ICPA and the LP-Heuristic (with both objectives), when we study problem instances derived from the basic problem instance in Section 4.5.

The time it takes the LP-Heuristic (for the different objectives) to find the solution is reasonable. We make the subjective remark that a calculation time for a tactical planning algorithm of under five minutes is more than reasonable, when related to the cost benefits and the time span during which the tactical plan is used. Furthermore, we see that the LP-Heuristic and ICPA have a different effect on the fluctuation coefficients. We see that the LP-Heuristic yields a lower deviation from average demand than ICPA. At the same time, ICPA yields a lower average difference of capacity demand between weeks. From subsequent experiments we find results similar to these observations for the behaviour of ICPA and the LP-Heuristic in terms of the fluctuation coefficients. The fluctuation measures are influenced by the fluctuation of the available regular capacity over weeks. The regular capacity does not fluctuate as much in a situation where all projects are considered and thus the real regular capacity per capacity group is considered, rather than the regular capacity minus the capacity already taken by projects not considered. *Figure 29*, *Figure 30*, and *Figure 31* depict the capacity requirements of the three departments with the highest total workload resulting from the various approaches of building a tactical plan.

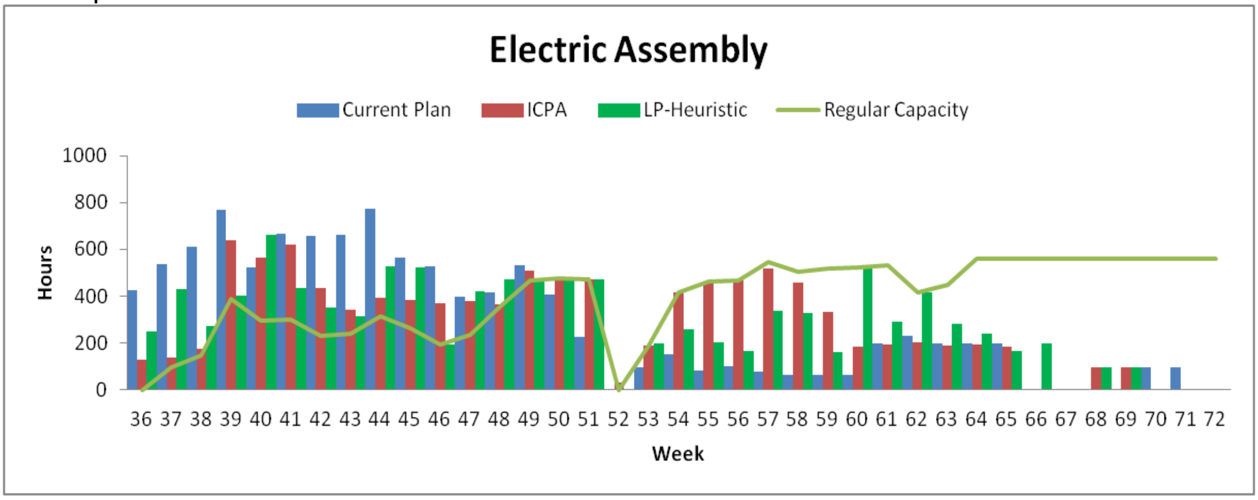


Figure 29: Capacity requirements for electric assembly

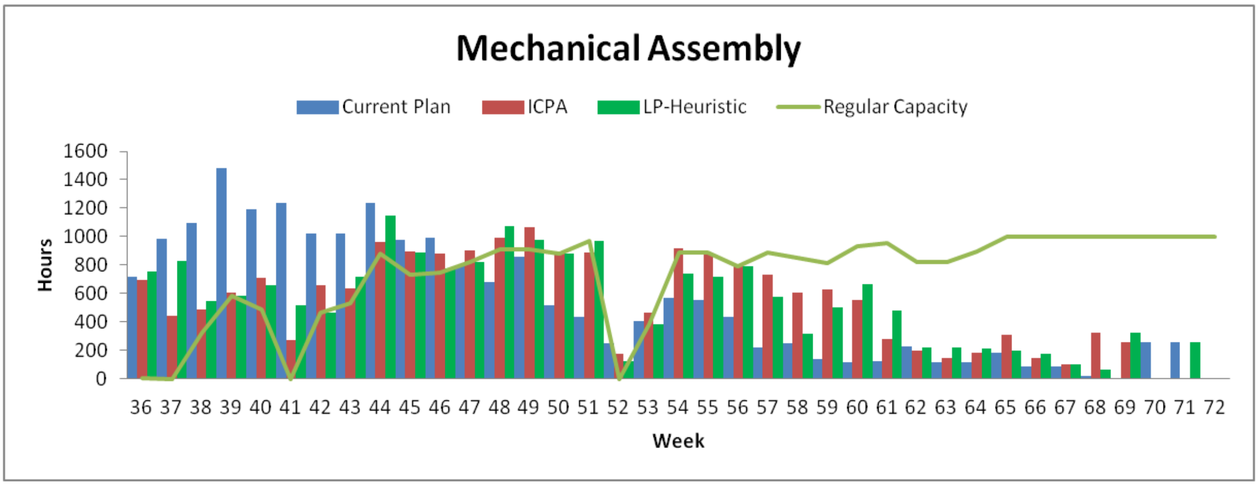


Figure 30: Capacity requirements for mechanical assembly

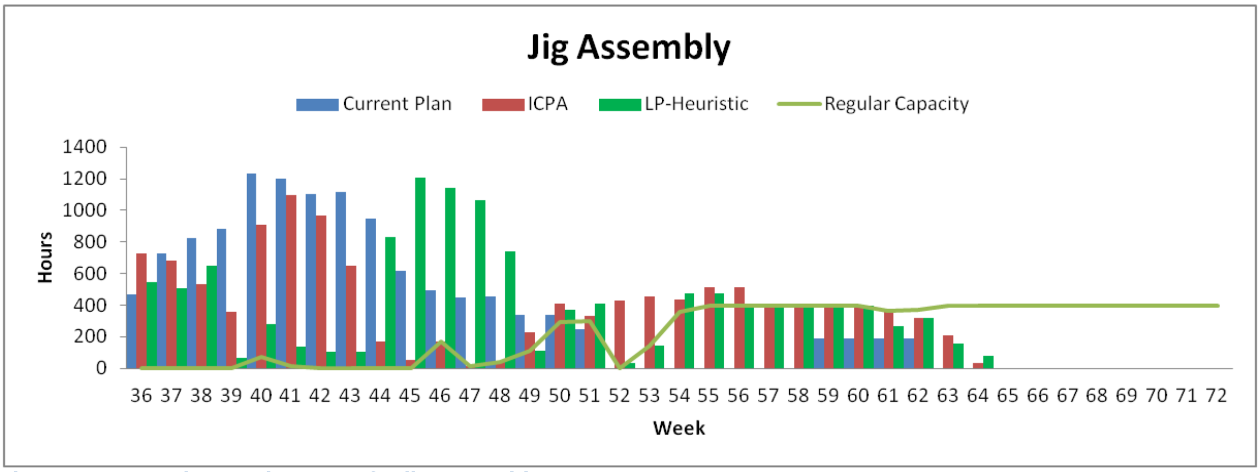


Figure 31: Capacity requirements for jig assembly

We already reach the conclusion that the substantial reduction in costs warrants an implementation of planning algorithms on the tactical level at AWL. Nevertheless, we need to further analyse the performance of the heuristics under different circumstances. Section 4.5 describes the effects of altering the base problem instance on the performance measures.

4.5 Sensitivity Analyses

This section observes the effects of altering several variables, such as the workload content of activities (Section 4.5.1), the due dates of projects (Section 4.5.2), the available regular capacity (Section 4.5.3), and the available non-regular capacity of various capacity groups (Section 4.5.4). The goal of this section is to observe how the algorithms perform under situations different from the situation discussed in Section 4.4.

4.5.1 Workload Variation

This section discusses the effects of altering the workload content of activities. The estimated workload for each activity in the base problem instance is multiplied by a number "X". For each value of "X", a new problem setting is created. The results drawn from these observations allow us to compare the performance of ICPA and the LP-Heuristic based on the "busyness" of the system. We assume, for simplicity, that the maximum number of workers that is allowed to work on an activity is proportional to the altered workload, i.e. the maximum workers is still defined by rounding up (the estimated workload / 40 hours)/(finish date in the original plan – start date in the original plan). *Appendix VIII* displays the full results of varying the workload in tabular form. We have varied "X" from .5 (halve workload) to 1.5 (50% extra workload compared to the base problem instance).

First, we observe that the difference in performance between the LP-Heuristic with an objective of minimising hours and the LP-Heuristic with an objective of minimising costs is slight. For 5 out of the 11 problem instances considered, the LP-Heuristic with the hours objective outperforms the LP-Heuristic with the cost objective on the cost objective. For 7 out of the 11 problem instances considered, the LP-Heuristic with the hours objective outperforms the LP-Heuristic with the cost objective on the hours objective. The differences found driven by both objectives, on both objectives, are always slight (<5%). The average time it takes for the LP-Heuristic to find a solution with the minimise hours objective for the considered problem instances is 67 seconds, for the minimise cost objective the average time to find a solution is 68 seconds. We conclude that it virtually does not matter which of the two objectives is used. Therefore, we only consider the results from the LP-Heuristic with the cost minimisation objective for experiments in the remainder of this section and consecutive sections of this report.

Figure 32 depicts the effect of varying workload on cost of non-regular hours. Both, ICPA and the LP-Heuristic with the objective of minimising costs, generate tactical plans for which the cost of non-regular hours increases as "X" increases. This is in line with expectations: when the total workload in the system increases, more non-regular hours are needed to meet all project due dates, and the cost of needed non-regular hours increases. We see that the LP-Heuristic always finds a tactical plan involving lower cost in comparison to the plan found by ICPA. The percentage with which the LP-Heuristic tactical plan outperforms the ICPA tactical plan varies. On average, for these eleven instances, the cost of non-regular hours for the LP-Heuristic are 14.9% lower than the cost of the ICPA tactical plan, with a minimum of 0.3% and a maximum of 25.8%. The varying relative performance of the LP-Heuristic to ICPA is due to the nature of the local search algorithm that might get stuck in local minima. It is possible that, when ATWs are sequentially altered according to an expected decrease in costs, a plan with no neighbour solutions that improve the objective (where the ATW of some activity is altered by one time-unit) results. Section 4.6.3 explains what local minima are and how certain search algorithms tend to get stuck in local minima.

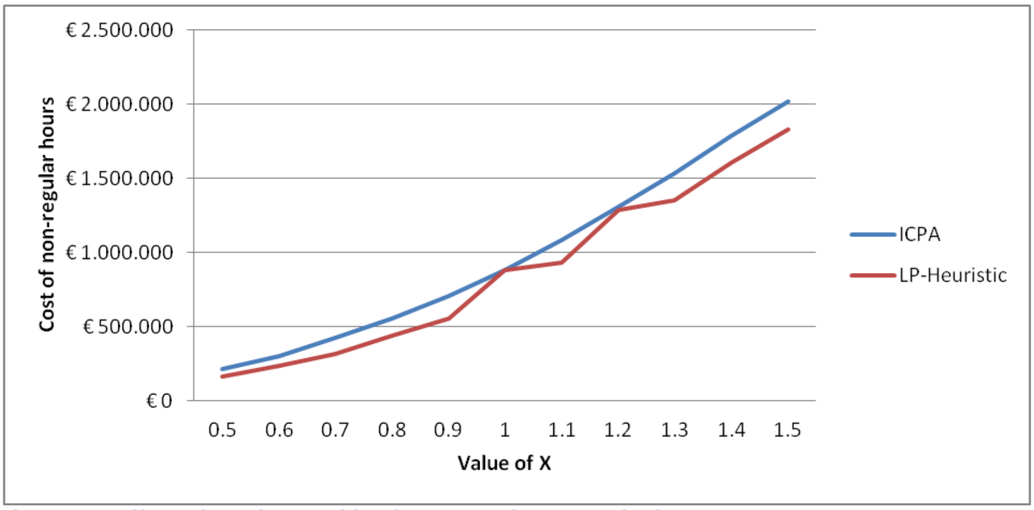


Figure 32: Effect of varying workload on cost of non-regular hours

From the results summarised in *Table 5* together with *Figure 32*, we also conclude that, if the LP-Heuristic was used for tactical planning, about a workload equal to 40% of the workload in the 18 considered projects could be added to the system at the same cost of the current tactical plan. 40% of the workload is 26.728 hours.

Appendix VIII shows the effects of varying workload on Fluctuation Coefficient I and Fluctuation Coefficient II. We see that both fluctuation measures tend to increase when the workload increases. ICPA, in comparison to the LP-heuristic, has a higher value for Fluctuation I, but a lower value for Fluctuation Coefficient II for all workload levels considered.

4.5.2 Due Date Variation

This section discusses the effect of the due date of a project on the cost of non-regular hours and the performance of ICPA and the LP-Heuristic with an objective of minimising costs. We vary the due dates of two projects with different characteristics. *Appendix IX* shows the full results of these analyses in tabular form.

A goal of this section is also to show how algorithms can aid an OA-decision. The due date of a project has an effect on the non-regular hours needed to perform that project and the other projects in the portfolio, given all constraints. Therefore, the due date that the sales department arranges with a customer has an effect on the cost of executing a project. Algorithms can help estimate the effect of varying the due date of a project on the costs of executing a project.

Table 6 shows the characteristics of the projects of which we have varied the due dates. Of the projects considered, we have chosen a project with relatively low workload and a low number of activities (p=3) and a project with a relatively high workload and a high number of activities (p=12). For both considered projects we perform multiple measurements where we vary the due date. For each project there are measurements focussed around the original due date and also covering the spectrum to the point where the project slack is equal to zero.

Project Characteristics	P=3	P=12
Total est. workload:	1.680 hours	7.040 hours
Number of activities:	20	123
Original project slack:	3 weeks (Due date = 50)	19 weeks (Due date = 71)

Table 6: Characteristics of considered projects

Figure 33 displays the effects of different due dates for project 3 on expected cost for non-regular capacity. The deadline of project 3 in the current plan is week 50. The earliest possible week the project could theoretically be finished, given the minimum durations, is week 47, i.e. the slack of project 3 in the current plan is 3 weeks.

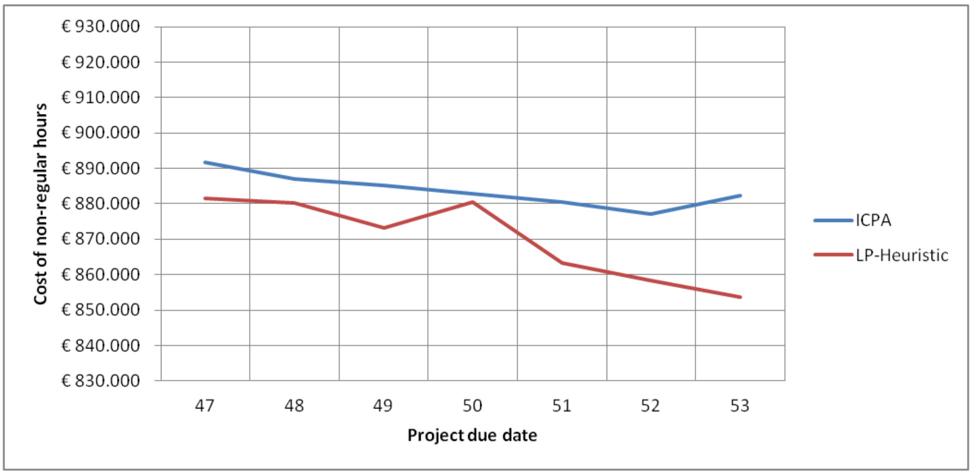


Figure 33: Effect of varying due date of project 3 on cost of non-regular hours

Figure 34 displays the effects of different due dates for project 12 on expected cost for non-regular capacity. The deadline of project 12 in the current plan is week 71. Given the minimum durations, the earliest possible week the project could theoretically be finished is week 52. The slack of project 12 in the current plan is 19 weeks.

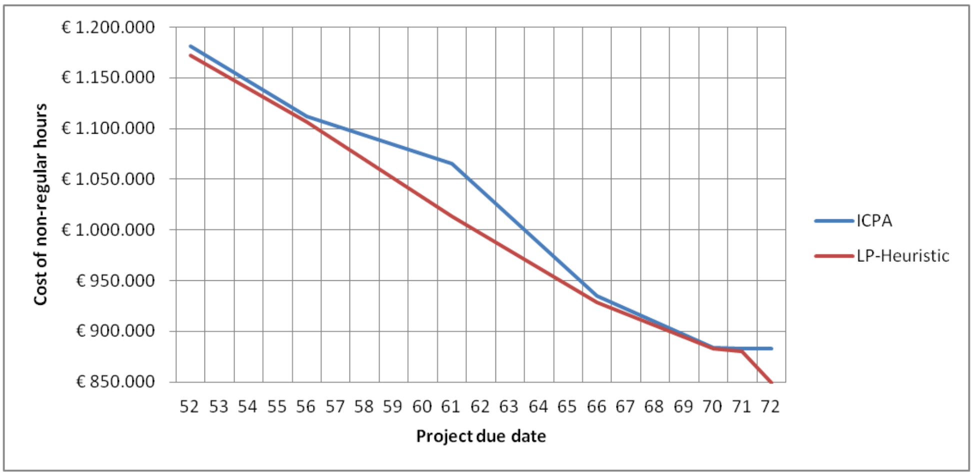


Figure 34: Effect of varying due date of project 12 on cost of non-regular hours

For both projects considered, in general, we see a decline in overall cost of a tactical project plan when the due date of a project is postponed. For both heuristics, there are some exceptions to this rule. For instance, in *Figure 33*, ICPA constructs a more expensive tactical plan when the due date of project 3 is week 53 than when the due date of project 3 is week 52. This is noteworthy, because the tactical plan constructed for a due date of 52 is also feasible when the due date of project 3 is week 53. This peculiarity is explained by the fact that both ICPA and the LP-Heuristic are heuristics. Heuristics do not necessarily find the best possible solution for the tactical planning problem. Heuristics do also not guarantee that a better solution is found when the solution space is larger. Section 4.6.3 explains what local minima are and how certain search algorithms tend to get stuck in local minima.

Figure 33 and *Figure 34* display that the effect of varying the due date of a bigger project (more workload and activities) is bigger than the effect of varying the due date of a smaller project. For instance, varying the due date one week results in an average cost difference of €3.979 for project 3 and €15.364 for project 12. If we couple this analysis to the economic concept of elasticity, we say that a project with higher workload is more elastic than a project with lower workload. Elasticity is the ratio between the percentual change of a dependent variable (in this case workload) to the percentual change of an independent variable (in this case the cost of a resulting tactical plan).

4.5.3 Regular Capacity Variation

This section discusses the effects of increasing regular capacity on the expected costs of non-regular capacity. *Appendix XI* displays the full results of the experiment. *Figure 35* summarises the data in graphical form. The x-axis displays the number of FTE we add in the experiment to one of the departments. By the addition of one FTE, the regular capacity of the capacity group increases by 40 hours over the full time horizon. The y-axis gives the cost involved with the tactical plan resulting from solving the base problem instance, extended with a certain number of FTE to a capacity group, with ICPA.

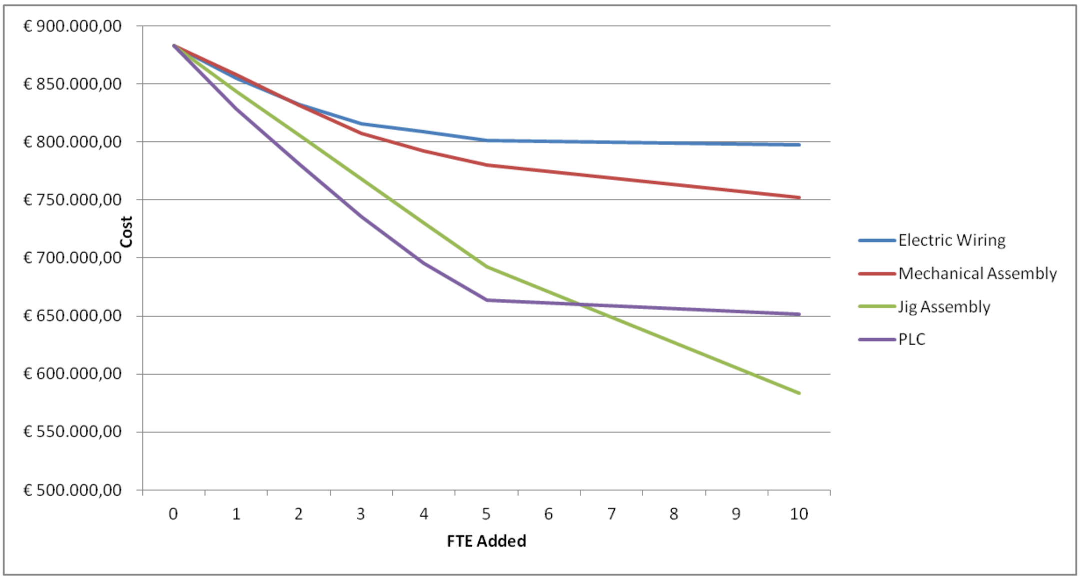


Figure 35: Effect of adding FTEs to several capacity groups on costs

The experiment considers the effect of adding an FTE to the regular capacity of four departments with the highest number of non-regular hours required when solving the base problem instance. The results show the benefits of adding one employee (for the problem instance considered). With such an analysis, over a longer period of time and considering all projects, AWL could calculate an estimation of how much they should be willing to invest in an FTE for a certain department.

The shadow price is the effect of marginally altering a constraint on the objective value. In this example the considered constraints are the regular capacities of the departments and the objective value is the costs of non-regular capacity. *Table 7* gives the shadow prices, or the expected benefit of adding on FTE to the regular capacity of a capacity group (given the problem instance considered).

Electric Wiring	Mechanical Assembly	Jig Assembly	PLC
27.987	25.082	39.501	54.140

Table 7: Shadow prices of regular capacity constraints

These results are an estimation of what AWL should be willing to spend on hiring one employee for the time horizon considered, which is 36 weeks. It is merely an estimation, because we only look at the 18 considered projects in isolation.

4.5.4 Non-Regular Capacity Variation

This section discusses the effects of varying non-regular capacity by employing the augmented version of ICPA. *Appendix X* gives an example of the working of Augmented ICPA. First, we consider the base problem instance and we vary the non-regular capacity constraints of all capacity groups at the same time. Next, we vary the non-regular capacity constraint of one capacity group. Finally, we consider an experiment with a small example, to get more insight into the effects of varying the non-regular capacity constraints in general.

The base problem instance considered in Section 4.2, is not suitable for analysing the working of Augmented ICPA. The current tactical plan often exceeds non-regular capacity restrictions. Because of the high workload in the problem instance, Augmented ICPA cannot find a solution for the base problem instance. To be able to do analyses with Augmented ICPA and the base problem instance, we multiply the level of the non-regular capacity restrictions of all capacity groups (as estimated in *Appendix I*) by a certain number "X". *Table 8* displays the results of the experiment and thus the effects on the various performance measures considered in this chapter.

Aug. ICPA	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
X=1.5	X	X	X	X
X=1.75	17.850	886.098	7.472	2.311
X=2	17.850	886.098	7.477	2.377
X=2.5	17.850	886.098	7.462	2.399
X=3	17.850	886.098	7.467	2.417
X=4	17.783	881.259	7.470	2.416
No restrictions	17.783	881.259	7.465	2.431

Table 8: Results of varying maximum non-regular capacity levels of all capacity groups simultaneously

The results show that the differences of various performance measurements are slight for different levels of allowed non-regular capacity. Between X=1.5 and X=3, the non-regular hours necessary for the plan, does not change. The value of X does have a minor influence on the resulting plan, which is reflected in the different values found for the fluctuation coefficients. We see that if we do not restrict the allowed non-regular capacity levels, that the resulting plan needs less non-regular hours and less costs.

From further analyses, it becomes clear that the non-regular capacity of the logistics department forms the bottleneck. For instance if we use X=1.75 to multiply the non-regular capacity restrictions of all capacity groups, but we add one FTE (40 hours) to the non-regular capacity restrictions of the logistics department, a plan is constructed with 17.783 non-regular hours needed and 881.259 costs.

To demonstrate the working of Augmented ICPA on the base problem instance further, we vary the maximum non-regular capacity for the electric wiring capacity group. In this experiment, the other capacity groups have no maximum to the non-regular capacity usage per week. *Table 9* shows the results. The first row in *Table 9* shows that if the maximum number of non-regular hours for electric wiring is set to 130 hours, Augmented ICPA does not find a feasible tactical plan.

Aug. ICPA	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
Max. 130 hours	X	X	X	X
Max. 135 hours	18.224	905.576	7.461	2.407
Max. 140 hours	18.246	906.503	7.462	2.408
Max. 145 hours	17.763	880.571	7.464	2.438
Max. 150 hours	17.783	881.259	7.466	2.440
No restrictions	17.783	881.259	7.465	2.431

Table 9: Results of varying maximum non-regular capacity limit of electric wiring

Table 9 shows that (in general) the lower the maximum level of allowed non-regular capacity for electric wiring, the higher the overall hours and costs needed for the tactical plan are. This is caused by the increasing non-regular capacity needed by other capacity groups. For some of the electric wiring activities, more weeks are needed to complete the activity, when the number of allowed non-regular hours for the capacity group is decreased. This means that activities before set electric wiring activity have to be finished sooner, or that activities after the electric wiring activity have to start later. This might cause that the activities in the same project as the electric wiring activity have to use more non-regular capacity.

From the experiments described so far in this section, and other experiments, we see that the base problem instance considered, is not very suitable for analysing the working of the Augmented ICPA. This is because much of the regular capacity of various capacity groups is already taken by other projects than the 18 considered projects in the first weeks of the time-horizon; there is usually not much room to decrease the latest allowed finishing time of an activity that precedes an activity that does not fit within the capacity constraints. This, and the complexity (if one bottleneck is abated, another one occurs) of the problem instance, makes that the effects of varying the non-regular capacity restrictions are small and that the window for varying the capacity restrictions is slight. Where we define the window for varying as the space between the non-regular capacity level for which Augmented ICPA cannot construct a feasible plan and the level where the shadow price of the capacity restriction is equal to zero. If the shadow price of the non-regular capacity restriction is equal to zero, it means that when the non-regular capacity linked to the capacity restriction is increased, the objective value does not change.

To discuss the performance of Augmented ICPA relative to ICPA and to analyse the behaviour of performance indicators when varying the non-regular capacity restrictions of capacity groups further, we also use a simpler example. The example exists of 6 projects, with each a maximum of 5 steps that need to be performed in serial. *Application I* is employed to perform the experiments (see *Appendix V* for the applications). *Appendix X* displays the results of the experiments in tabular form. From the experiment, we conclude that the effect of varying non-regular capacity restrictions on the performance indicators is difficult to predict. For some settings, the restrictions on the maximum non-regular capacity levels will guide Augmented ICPA into constructing a tactical plan with a better performance on the performance measures, other settings will have little effect on the performance measures. Some non-regular capacity restrictions will worsen the relative performance of the tactical plan, mainly if the limit of when Augmented ICPA can find a feasible plan is approached.

4.6 Discussion Of Results

This section discusses the results from Section 4.4 and Section 4.5. Section 4.6.1 discusses the revenues that AWL can expect by the employment of a new tactical planning system. Section 4.6.2 discusses the effects of tactical plans resulting from algorithms on capacity groups. Section

4.6.3 discusses the varying performance of the LP-Heuristic. Section 4.6.4 concludes Chapter 4 with a summary.

4.6.1 Expected Revenues

This section discusses the expected revenues that are obtained by AWL, if AWL employs algorithms for tactical multi-project planning. As mentioned in Section 4.4, based on the results of the experiment, we cannot simply jump to the conclusion that the LP-Heuristic will reduce the costs for the tactical plan with 45%, compared to the original plan.

The first reason is that we have only considered one problem instance to compare the heuristics to the current tactical plan. One could argue that the problem instance might be biased and that the resulting average savings might be somewhat different if multiple realistic problem instances were considered. However, because of time-constraints of this research and impaired data collection possibilities (recall Section 4.2), we are only able to consider one problem instance for which comparison to the current situation is possible. The problem instance considered is based on reality and fairly complex (18 projects, 654 activities). The complexity of the problem instance renders that possible bias, caused by unordinary projects for instance, is reduced by a neutralising effect of other projects.

Another reason why we cannot simply state that we expect a 45% reduction in costs is that we have not considered all projects during the considered time-horizon. If we had considered these projects, the expected result is that the savings are even higher. The costs would be lowered if we consider all projects, because the effect of multi-project planning would increase, because the solution space for the heuristic to construct a favourable tactical plan would increase. It is difficult to estimate by how much costs would decrease if all projects are considered. At the same time, the computation times for the heuristics increase if more projects are considered.

The restrictive assumption that the maximum number of workers assigned to an activity in the current tactical plan is the maximum number of workers allowed to work on this activity at the same time, as well as the restriction that the experiment does not include all projects, limits the solution space and therefore limits the potential for the cost savings. Recall that the maximum proportion of the workload of an activity that is assigned to a time-slot, divided by 40 (hours of an FTE), and rounded up to the nearest integer, defines the maximum allowed number of workers. In reality, however, the number of workers that are allowed to work on an activity at the same time might be larger. If the actual allowed workers at the same time is higher for some activity, resulting plans improve and associated costs decrease.

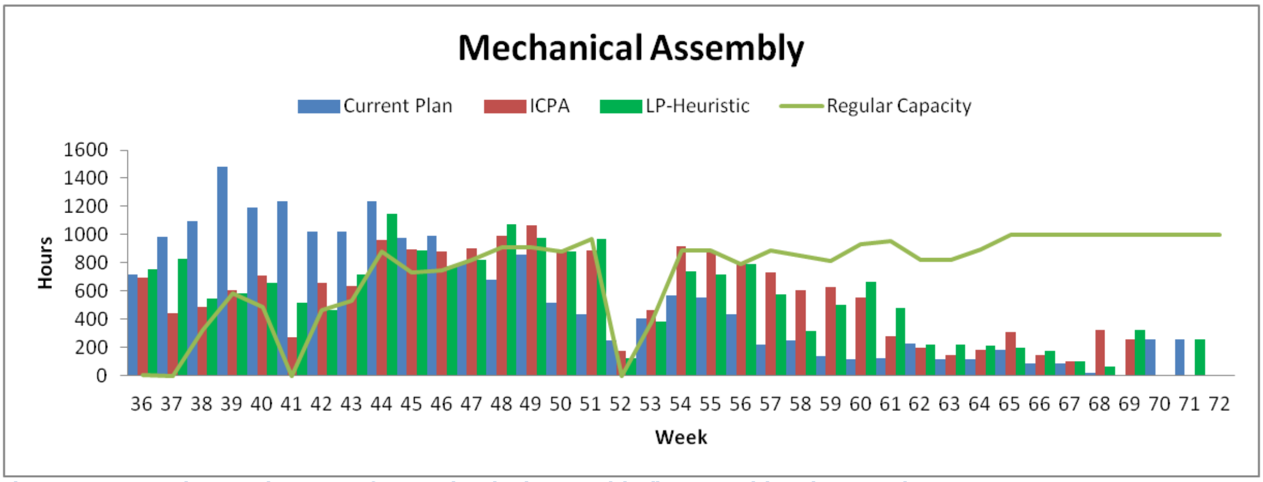


Figure 36: Capacity requirements for mechanical assembly (base problem instance)

Figure 36 shows that both heuristics exhibit the feature that more workload tends to be planned later in time in comparison to the current plan. Plans resulting from the heuristics consume more regular capacity in later weeks, e.g., week 54 to week 60. In the likely event that new business opportunities (projects) occur after week 36, there is less regular capacity available for these new projects in the tactical plans resulting from the heuristics, than in the current tactical plan. So, we have to take into account that the estimated 45% reduction in cost of non-regular capacity comes at a price of more occupied regular capacity and thus less space for new projects. It is difficult to translate this effect into costs. An option is to estimate the value of free regular hours for capacity groups in a certain week and add costs to the costs of a tactical plan for each hour of regular capacity taken. Currently, at AWL, such estimates are not available and it goes beyond the scope of this research to make a proposition for such estimates. AWL would benefit from inclusion of the cost of using regular capacity into their measure for determining the cost of a tactical plan.

Related to the issue that the heuristics tend to plan relatively more workload closer to the due date of the project than the current tactical plan, is the observation that the ability of the heuristic plans to absorb unforeseen setbacks at the end of a project is smaller. In general, the current tactical planning method plans more slack at the end of projects, so that when milestones are not met by early activities, or unforeseen setbacks occur, the successive activities have enough time to make up for the setbacks. Unforeseen setbacks early in the project, however, will result in unmet milestones more often with the current method of planning, in comparison to the heuristic methods.

Because the notion that a 45% costs reduction can be reached is challenged by the aforementioned points, we employ a somewhat subjective but save window for the estimated cost reduction that is obtained by employing the LP-Heuristic of 30% to 50%. From January 2011 to July 2013, the cost of overtime spend by departments involved in direct project activities was 5.3 million euro. This means an average yearly cost of 2.12 million. So, assuming the same level of business in the future, employing a heuristic to make tactical plans could save AWL between €636.000 and €1.060.000 on a yearly basis. Or, AWL could accept more projects at the same costs of non-regular capacity. The costs of developing and maintaining the new planning system have to be detracted from these results. It has to be noted that the yearly savings interval is based on a comparison of the tactical plans, which is only an estimation of the realisation of these plans on the operational level.

4.6.2 Discussion Of Resulting Tactical Plans

This section discusses the tactical plans that result from the various heuristics in our analyses. A critical look at the plans unveils peculiarities of the plans that have to be taken into account. Figure 37 depicts the capacity requirements for the PLC department resulting from the various approaches of building a tactical plan.

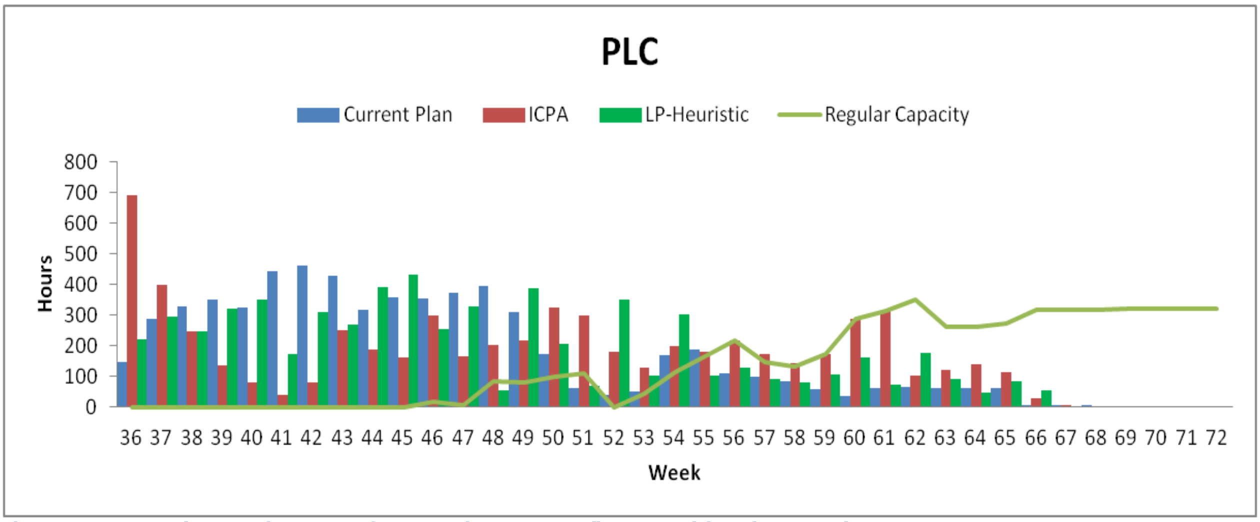


Figure 37: Capacity requirements for PLC department (base problem instance)

In week 36 we see an unfavourable feature of ICPA, namely that the "plan as much as soon as possible principle" results in a high peak in demand for PLC-workers. In reality, this is a peak that cannot be filled. The peak for non-regular demand in week 36 does not directly come at a price, because all regular capacity for the following weeks has already been used up by projects other than the 18 considered in the experiments. From the capacity requirements resulting from the LP-Heuristic, however, we find that an unrealistic peak in week 36 is not necessary for enabling a tactical plan with competitive overall cost. Recall that the costs associated with the ICPA plan is 882.960 and the costs associated with the LP-Heuristic plan (with the objective of minimising costs) is 880.501. Defining borders to the use of non-regular capacity and employing of Augmented ICPA would result in the elimination of unwanted peaks.

Figure 38 displays the project plans that result from the various approaches discussed, for project 5 of the base problem instance. To be more precise, for each activity, the bar ranges from the first week in which a proportion of the workload for an activity is planned, to the last week in which a proportion of the workload is planned. We see, that some activities later in the project are planned later in time by the heuristics than in the original tactical plan. This observation is in line with the observation from the capacity graphs that the heuristics tend to plan relatively more workload closer to the due date of the project than the current tactical plan.

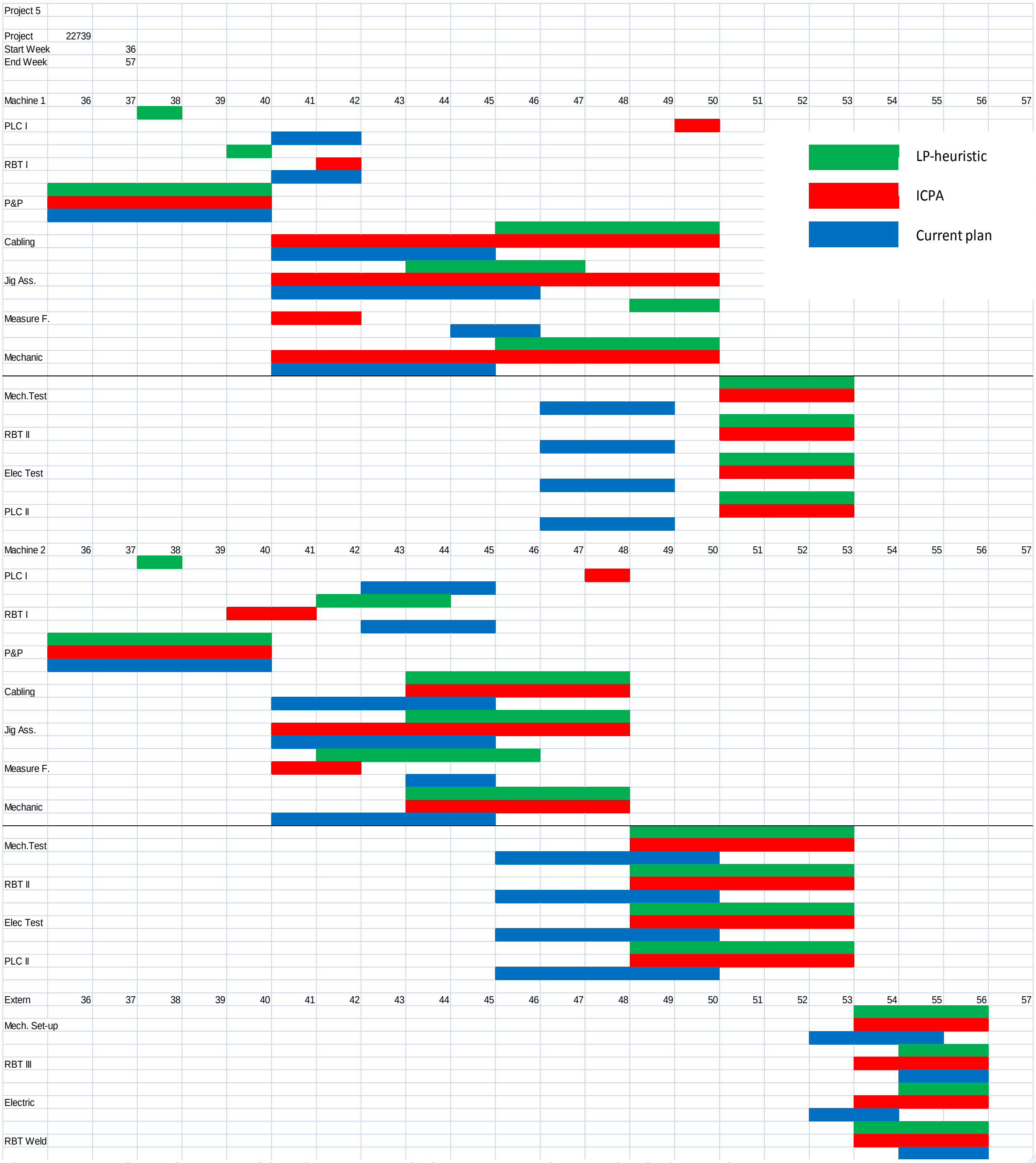


Figure 38: Project plans resulting from several plan construction methods for project 5

Another observation that we make from *Figure 38*, is that the duration or cycle time of activities can change. *Figure 38* gives examples of both increasing and decreasing activity cycle times. Increasing cycle times might lead to the undesirable effect that work-in-process remains "on the floor" for a longer period of time. For activities in the project where something is physically built, this means that the necessary space is required for a longer period of time. Another disadvantage of longer activity cycle times is that, in general, workers have to work on more activities in parallel (they have to divide their focus and attention).

The throughput of the system, i.e. the number of completed activities in a time period, stays the same (if we compare the current plan to the heuristic solutions), since all activities have to be finished in time to meet the project deadline. We deduce from Little's Law that the WIP, i.e. the number of active activities in the system, increases with the same rate as the rate with which the cycle times of activities increase. Little's Law states: *Cycle Time x Throughput=Work In Process*. Since we observe from *Figure 38* that the average cycle time of activities might change (if we compare the current plan to the heuristic plans), we are curious about the WIP in various weeks at several departments. We define an active activity as an activity that has a start time ≤ *T* and an end time ≥ *T*, where *T* is the current week. It is not necessarily the case that any work is done in week T on active activity. *Figure 39* displays the number of active activities per week for several capacity groups. *Figure 39* compares the current tactical plan to the tactical plan resulting from ICPA.

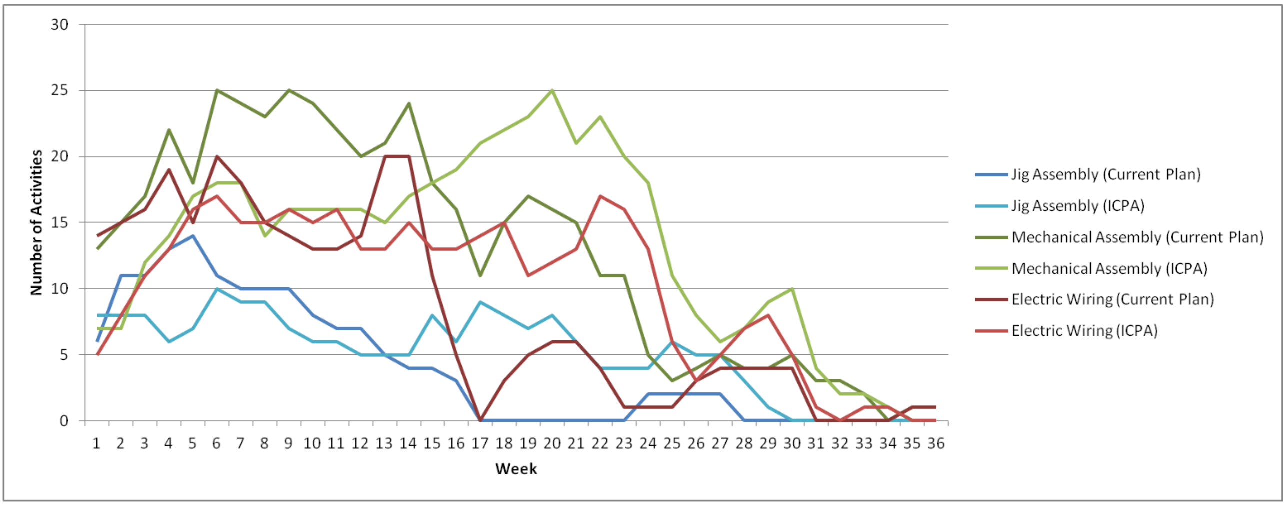


Figure 39: Number of active activities per week for several capacity groups resulting from various planning approaches

Figure 39 displays that the number of active activities in a week in the two plans can differ significantly. The peaks in active activities over time for the considered resource group does not differ much. On average (if we compare the current plan to the ICPA plan), the active activities for the Jig Assembly increases by 1.2, Mechanical Assembly by 0.3, and Electric wiring by 2.1. On average, over all sixteen considered capacity groups, the number of active activities per week decrease by .7. So, for some capacity groups the average number of activities is somewhat lower in the ICPA plan in comparison to the current tactical plan.

4.6.3 Discussion Of Varying The LP-Heuristic Performance

This section discusses the effects of a first fit search approach on performance of the LP-Heuristic. With a varying performance we mean that the relative difference of the LP-Heuristic solution to the ICPA solution varies. The varying performance of the LP-Heuristic is caused by a characteristic of the local search algorithm employed by the LP-Heuristic, that it cannot escape local optima. *Figure 40* displays an example (unrelated to AWL) were two independent variables determine the objective value (dependent variable) of an optimisation problem.

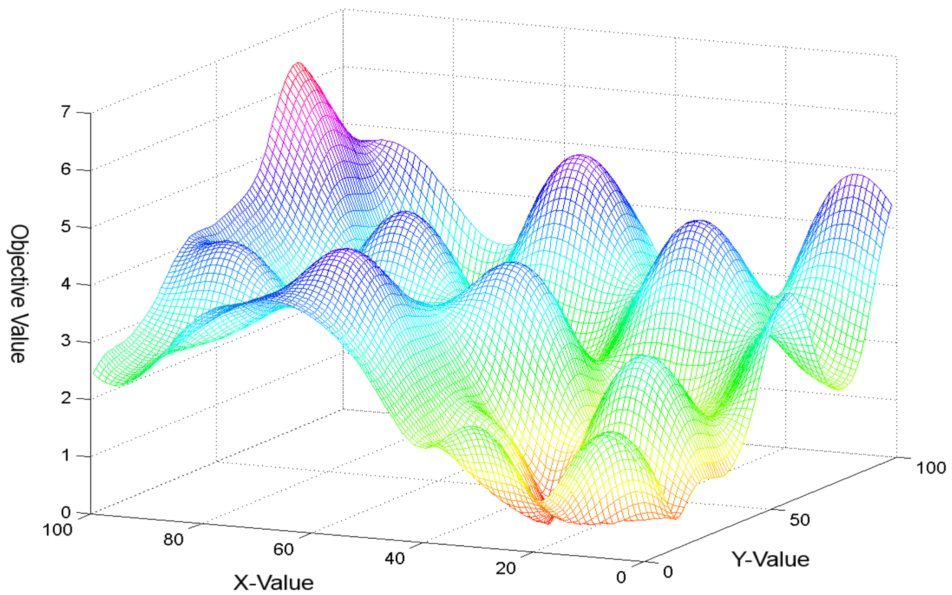


Figure 40: Solution space example

A local search algorithm starts from an initial solution. This solution is defined by a certain value of the independent variables. The goal of a local search algorithm is to minimise the objective value. The local search algorithm employed in the LP-Heuristic employs a first fit approach, which means that neighbour solutions are created by slightly altering the values of variables, and then the first neighbour solution with a lower objective value is picked. The picked solution is used as a new starting point for the local search. This iterative approach continues until no neighbours are found with an improved objective value.

In *Figure 40*, we consider a situation where the starting solution is determined by an X-Value of 90 and a Y-value of 25. The objective value corresponding with these values is 3.8. If the first fit approach is employed, the solution found by the approach is defined by X=95 and Y=0, with an objective value of 2. We see, however, that this is only a so-called local minimum. We find a minimum objective value of .5 by setting the variables to X=20 and Y=5. We conclude that a first fit search algorithm is not always able to find the best solution.

For the tactical planning situation at AWL, because of the varying relative performance of the LP-Heuristic, it would be fruitful to employ a search algorithm that is able to escape local minima. Furthermore, it is wise to perform several calculations to determine a tactical plan with various objectives, so that there are a number of tactical plans with different characteristics to choose from. The downside of these measures is that the computation time will increase.

4.6.4 Summarising Results

This section summarises the results from the experiments in Chapter 4. For the base problem instance considered, a 45% reduction in costs of non-regular capacity is reached by employing the LP-Heuristic to construct a multi-project tactical plan. We put this result into perspective and reach the conclusion that a 30% to 50% reduction in costs of non-regular hours is realistic, on the long run, assuming the same level of business in the future. This means that, employing a heuristic to make tactical plans could save AWL between €636.000 and €1.060.000 on a yearly basis. Section 4.5 describes several sensitivity analyses. These analyses show the performance of the considered planning algorithms under different circumstances. These analyses also show how planning algorithms are employed to get an insight into the effects of strategic or tactical decisions, such as the acceptance of an order, or the decision to increase capacity. All in all, we conclude that there is a lot of potential to save costs and to get a better insight into operations at AWL, if algorithms are employed to construct multi-project tactical plans. The relative ease with which a plan is produced, makes it easier to revise a plan when new information or unforeseen events occur.

Chapter 5: Implementation

This chapter describes what considerations AWL should take into account when implementing a new tactical planning system and how to do this. Chapters 2 and 4 show the necessity for AWL to use algorithms for tactical planning.

Section 5.1 discusses how AWL should ensure proper input data for a planning system. Section 5.2 explains that the tactical planning function should do centralised planning in order to perform multi-project planning. Section 5.3 describes the operational effects of a new planning system. Section 5.4 discusses the requirements of a new software package for planning. Section 5.5 discusses the issues of creating awareness and support for a new planning system. Section 5.6 discusses the possible costs and risks associated with implementing a new planning system. Section 5.7 describes the 8 steps by Kotter (1995), that should be kept in mind for a proper management of the project.

5.1 Elimination Of Data Ambiguity & Standardisation

This section discusses the prerequisites with regard to data for implementing a planning algorithm for (tactical) planning. Guaranteeing quality data and unambiguous data is essential as input for a tactical planning algorithm. The algorithm has to be coupled with AWL's ERP-system: Navision, and the operational scheduling software tool: AWL-planner. This means that the data needed for the algorithm should be linked to the data in Navision and the AWL-planner.

Currently, some of the data or information needed for the algorithm is missing or ambiguous in the existing planning systems. First of all, the precedence relations between a project's activities are not specified. The tactical planner knows in which order the activities of a project should be performed and plans accordingly. There are, however, slight differences in precedence relations between projects. From a project plan, it is impossible to retrieve whether an activity is planned after another activity, because there is a necessary technical precedence relation, or just by accident and the activities have no direct relation. AWL should map the technological precedence constraints between activities in a project precisely. Technological precedence constraints between activities are relations where a set of activities have to be finished before the next set of activities can start. These technological precedence relations should not be confused with planning choices. If a department prefers to do a set of activities in a certain order, maybe because of historical reasons, but it is not strictly necessary to do them in that order, then these are not technological precedence constraints.

Another problem is that sometimes related activities overlap. The tactical planner estimates in certain cases that if an activity is finished for 80% the successive activity can already start. This line of reasoning cannot be retrieved from the planning system. These special type of precedence relations should be known and it should be possible to retrieve them from the planning system. An example of a delayed precedence relation is the relation between the activities cabinet building and wiring, where wiring can start when cabinet building is "almost ready". Although, it might be somewhat subjective to define an exact percentage of the workload of an activity that has to be performed, before a next activity can start, it is important for a planning system to incorporate these rules. A planning algorithm uses this information to set the ATW windows. For instance, if an activity can start after its predecessor is finished for 80%, the earliest allowed starting time of the activity is set accordingly (so the *t* where the predecessor is 80% finished +*1*).

A project consists of machines and the machine consists of (multiple-levels of) elements. Some activities have to be performed for different elements. These activities have the same ID in the current planning system and therefore it is difficult to distinguish between them. Especially for some activity types, that are not explicitly linked to an element in the system, but in practice belong to a certain element.

Currently at AWL, the maximum number of workers is known or estimated by planners, but this number is not recorded or documented. There is a maximum to the number of workers that can perform the same activity at the same time. If this number is exceeded, workers cannot work efficiently. Algorithms for the RCCP need the maximum number of workers that can work on an activity at the same time as an input. If this restriction is not added, the algorithm might yield unworkable solutions.

As discussed in Section 4.3, the durations of activities in the process optimisation phase and the external phase are determined somewhat differently than durations of other activities. Because of the uncertainty and the iterative nature of the activities, it is unrealistic to determine the minimum duration of these activities by simply dividing the workload by the number of FTE's that can work on the activity at the same time (FTE*40). Therefore, a minimum duration of these activities has to be defined.

Another issue that could be included is the division of an activity's workload over its duration. For instance, for the work preparation activity, the most amount of man hours is put in at the beginning of the activity duration. This is because the activity duration of the work preparation activity includes the delivery time of the customer. Another example is the project management activity, which was not included in our experiments, because the activity has no direct predecessors or successors, and the workload of the activity has to be divided in a certain manner over the whole period. Defining rules for the division of an activity's workload is important, in order to make sure a tactical plan resulting from an algorithm does not result in an unworkable division of the activity's workload.

Section 4.6.2 also exposes that planning algorithms might increase the work-in-process for some departments, because the ATWs stretch. For instance, Jig Assembly, has a maximum number of work spaces. Therefore, it might be wise to determine a maximum number of activities that is worked on at one unit in time, for certain activity types or capacity groups.

When, after the start of the project, extra activities need to be added (because of new insights at engineering or changes in client requirements), this is currently done without linking the new activity to an element or other activities. Therefore, it is unclear what activities have to be finished before a new activity can start.

Summarising the preceding comments, we recommend:

- Precedence relations between activities should be included.
- Delayed precedence constraints should be made explicit.
- Activities should be linked to the corresponding element clearly.
- Precedence relations between elements should be included.
- Maximum number of workers per activity has to be defined
- Minimum duration of optimisation and external activities have to be defined.
- Rules for the division of workload over the activity duration should be included.
- Maximum number of activities in process per capacity group and activity type.
- New activities have to be added to the existing project activity hierarchy.

It is not necessary to define these precedence relations and other rules anew, every time a new project is to be planned. Because many projects show similarities, especially projects of the same type or repeat orders, templates could be used for different kinds of projects. These templates consist of a set of rules to which a planning algorithm must adhere if such a project is planned. Employing templates saves time, because the rules-set would not have to be made from scratch every time a new project is handled. It is important that the tactical planning function knows these templates and has a good knowledge of whether a template is suitable and what extensions or alterations are suitable in a specific case. These templates have to be managed. If problems occur during the execution of a project, the tactical planning function should analyse how this problem has occurred and how this problem should be prevented from happening again in the future. This might lead to a revision of a template. The idea of using templates for tactical planning of projects, is in line with developments at AWL to standardise more. Section 2.1.2

explains that AWL aims to move from an ETO organisation to a more CTO oriented organisation (at least for certain projects).

Section 2.3 describes what KPIs have to be measured to measure the performance of (tactical) planning and operational performance in general. Performance measurement is key to judge the performance of a (new) tactical planning system. Flaws in the system are exposed by actively judging performance. Based on performance management, continuous improvement of the system is possible.

All in all, the data structure needed for planning should be clearly defined and all ambiguities should be eliminated. This task has to be performed to be able to plan using algorithms. The use of templates, which define the planning rules for a project, could be useful for saving time in defining the rules for a new project.

5.2 Tactical Planning Function

This section discusses what responsibilities and tasks the tactical planning function should have when employing a new algorithm based tactical planning system. Furthermore, this section discusses what changes in the tactical planning function at AWL are necessary to make sure that the tactical planning function can fulfil their responsibilities and tasks.

Section 2.2.1 discusses the hierarchical planning framework and how planning roles and responsibilities are currently divided within AWL. From Section 2.1.1 we conclude that the current situation (on the leftmost side of *Figure 41*) is not ideal. Currently, the resource-constrained project scheduling is the responsibility of the project leaders, because the planning responsibilities of a project are handed over from the planner to the project leader at the start of the project. It is not ideal to put the responsibility of resource-constrained project scheduling in the hands of the project leaders, because there are multiple projects and multiple project leaders. This makes multiple-project planning at the “early” operational stage impossible, and therefore makes it impossible to efficiently manage the capacity usage of resources. We propose that the tactical planner or a planning department should be responsible for maintaining or updating the schedules of projects and that project leaders are responsible for adhering to schedules and reporting deviations from the planning (aside from their other tasks). This would also make it possible for the planner to re-plan running projects to efficiently “fit in” a new project.

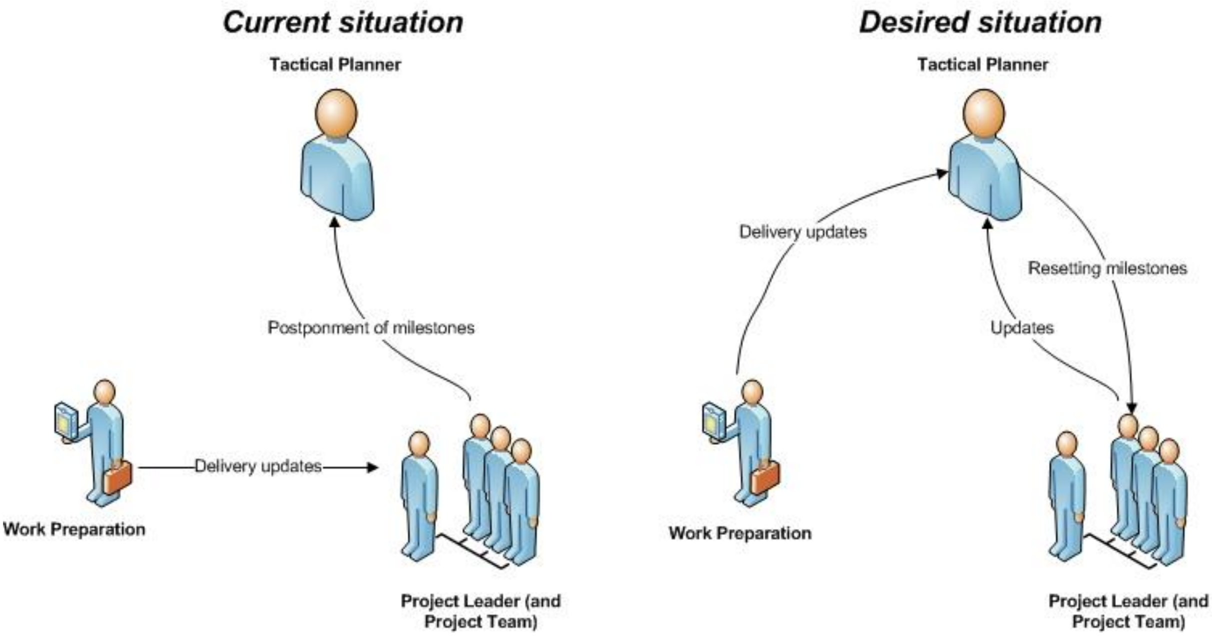


Figure 41: Necessary change in communication lines for tactical planning function in order to enable multi-project planning

Restructuring the planning function to make multi-project planning possible, requires the project leaders to provide timely updates on changes in the expected workload of activities and Procurement/Work Preparation should monitor deliveries and report to the tactical planner if deliveries are (expected to be) late. *Figure 41* depicts the necessary change in communication lines. Whereas in the current situation, the project leader proposes a shift of a milestone (if necessary) to the tactical planner, AWL should go to a situation where the tactical planner re-plans projects from a multi-project perspective. This means that the tactical planner needs to have all necessary information available. Therefore, Procurement and Work Preparation have to report delivery statuses to the tactical planner, instead of to the project leaders (as in the current situation). Furthermore, the project leaders should filter and pass on information they receive from their project team about changes in expected workload of activities, or information from the customer about changed deadlines. This would make it possible for the tactical planner to plan projects on a multi-project base.

The proposed redesign shows similarities with a concept called portfolio planning, proposed by Platje et al. (1994). A portfolio is defined as: “a set of projects which are managed in a coordinated way to deliver benefits which would not be possible if the projects were managed independently” (Platje et al., 1994). Portfolio (organisation-wide) goals should be placed before the goals of individual projects. Platje et al. (1994) propose a portfolio management team, consisting of department heads, project leaders, and the tactical planners. Such a portfolio team meeting provides one mode of communication, instead of many informal bilateral lines.

The team meets periodically to decide on a tactical plan and goals. Platje et al. (1994) do not elaborate on how exactly a feasible rough-cut capacity plan results from such a portfolio management team meeting. Logically, however, the actual rough-cut capacity plan is the responsibility of the tactical planner, who is to propose a tactical plan at the beginning of such a meeting and later adjust it based on surfaced issues during the meeting.

The approach to have periodical meetings also has its drawbacks. For instance, if a meeting of such a type was to be set up at AWL, with all project leaders, department heads, and the tactical planner, then the likeliness of deviating from the core subject of the conversation is high. Furthermore, when the subject of conversation is the postponement of a certain milestone of a certain project, the projects of other project leaders might not be effected and they would be wasting their time attending the meeting. Therefore, it is better if project leaders and department heads get (formalised) responsibility to give the tactical planner the information or data he needs. The exchange of information between the planner and others can also be done through bilateral communication, when an issue occurs. Because of the increase in responsibilities for the tactical planning function that we propose, it is necessary to expand the staff of the tactical planning function. Currently, the tactical planning function is performed by one person. If this person is absent, his responsibilities are taken up by someone with other tasks and less knowledge of tactical planning choices.

To summarise, we propose that a central tactical planning function is responsible for the rough-cut capacity planning, as well as resource-constrained project planning. The central planning function is able to plan from a multi-project perspective, which is important to efficiently use the organisation’s resources and to reach organisational goals, instead of just looking at the interests of one project in isolation. It is important that clear communication structures are built, in order to make sure that the tactical planning function possesses all relevant information to make the best planning decisions possible. Information such as described in Section 5.1, but also information about capacity availability and information about deliveries and unforeseen setbacks. Uncertainty and volatility which reveals itself in the operational phase of a project, can be reduced and contained by timely gathering and processing of relevant information in earlier planning stages.

5.3 Implications For Operational Scheduling

This section discusses the implications of a new algorithm based tactical planning system for operational schedulers and operations in general. The tactical planning function is not an isolated function. The tactical plan defines the boundaries in which a department schedule has to be produced. Currently, the role of department schedulers is to divide the workload of an activity over time, such that the activity deadline, as defined in the tactical plan, is met. In the proposed new situation, the tactical plan already defines how workload of an activity is spread within its time-window. The operational scheduler should not make big changes to this workload division, because the effects of the multi-project based premises will be nullified. In other words, a certain workload division, resulting from a tactical planning algorithm, was chosen to ultimately utilise resources and reduce the costs of non-regular workers. If an operational scheduler is to change this division, these effects might be lost. On the other hand, since there is more information available at the operational scheduling stage, and the operational scheduler has more restrictions and detail to take into account, the operational scheduler should get some freedom to deviate from the tactical plan. It is difficult to exactly define the breathing space of the operational scheduler. A mode of working should be found, where an operational scheduler understands the effects on the overall picture, if he chooses to deviate from the tactical plan.

Creating a new tactical plan has the potential to completely change the operational schedules. It is undesirable if a new tactical plan changes the schedule of a certain department for the next day completely, because employees are likely to have made arrangements that fit their schedule. Also, if a new tactical plan imposes different restrictions to an operational schedule on the short term, the operational scheduler must do his work of making a schedule again, which is a waste of time and effort. Therefore, we propose that a new version of the tactical plan is not allowed to alter the plan of the current and the next week. This is in line with the current way of working at AWL, where a schedule is built for a maximum of 2 weeks in advance.

The operational scheduling method should be reassessed. In Section 2.4, problems are observed with the time it takes to schedule, the detail with which there has to be scheduled, and the multi-project overview that is missing in the scheduling software. It is not within the scope of this research to address these problems in detail, or come up with solutions. It is, however, intuitively clear that many of the reasoning, of why and how algorithms are useful for tactical planning, also applies to operational scheduling. In an ultimate (almost Utopian) vision of the future, AWL has a real-time adaptive (operational) system where deviations from the plan are introduced to the system and a new ultimate master plan (tactical level, as well as, operational level) is generated instantaneously. The first step, however, is to improve the tactical planning method by employing algorithms.

5.4 Software

This section discusses what specifications tactical planning software should have and what considerations should be taken into account when developing the software. Based on the set of software specifications, AWL has to make a make-or-buy decision. Both options have its advantages and disadvantages, but a prerequisite of making the software in-house is the necessary knowledge. It is doubtful that AWL has the expertise and experience with software development and planning algorithms to make such a software package internally. There are organisations that specialise in building company specific planning software. Expertise of this type of company has a price tag (Section 5.6), but it will also reduce the risk of errors and increase the quality of the package. An assessment and cost-benefit analyses of possible partners for developing the software together with AWL should be made. Actors that are going to work directly with the new system, such as the tactical planning function, IT, and the department schedulers, need to be involved in the development of the tactical planning system.

The planning software should fit the operational scheduling software at AWL (the AWL planner), or it should incorporate a new operational scheduling system. Since we have established that the current operational scheduling method at AWL has its flaws (in Section 2.4), it might be wise to hit two birds with one stone and build a planning system, which has the operational scheduling functionalities included. The planning system should be ready for the future, so if AWL decides to schedule differently on the operational level from the current situation, for instance with algorithms, these changes should be easy to make.

The interface of the software package should give a quick overview of the requirements of all capacity groups. It should be easy to change a plan on the tactical or operational planning level and the effects of such a change on the overall capacity requirements of a department should be visible. It should also be possible to change the planning restrictions of one or more projects at any time and let the algorithm create a new plan. The effects of adding a certain project to the portfolio on capacity requirements, given certain constraints, should also be insightful. The (added) effects of a planning decision on performance measures, such as cost of non-regular capacity or the effects on both fluctuation coefficients described in Section 4.1 should be visible.

There are also some requirements to the algorithm employed in a new software system. The algorithms used in Chapter 4 are not as powerful as, for instance, a branch-and-price algorithm. However, the computation time of such an algorithm for solving an AWL tactical planning problem is unknown, but will be higher than the computation time of the LP-Heuristic. If AWL (perhaps in cooperation with a software vendor) decides to employ an algorithm with a potentially high calculation time, it should be possible for the user of the software to indicate a maximum computation time for a new plan. Section 4.6.3 concludes that, it could be fruitful to employ a search algorithm that is able to escape local minima. Furthermore, it might be wise to perform several calculations (with, e.g., different algorithms) to determine a tactical plan with different objectives, so that there are a number of tactical plans with different characteristics to choose from.

The possibility of including the uncertainty of the workload of an activity must be present in a new software system. Section 3.2.4 and Section 3.2.5 discuss two algorithms with two different approaches to incorporate uncertainty. Even though proper research into how AWL can best incorporate uncertainty of the workload of activities must still be performed, a new planning software package should include the possibility to incorporate uncertainty. When the time is ripe, AWL can use this option. Recall from Section 2.7.3 that incorporating uncertainty can lead to a robust tactical plan. A robust plan is as insensitive to uncertainty as possible.

It goes without saying that all planning algorithms employed must adhere to the planning restrictions. The user of the system should be allowed to break a restriction in a plan if he has good reasons, but the planning software should alert the user if he does. So, for instance, if the user decides to move a job ahead one week in time and hereby breaks a precedence relation, the user should be warned. The idea is that by creating trust, at users, in the planning system, the user will not often change the resulting plan.

5.5 Creating Awareness & Support

This section discusses why and how awareness and support should be created. In this context, awareness is the notion that tactical planning with the help of algorithms is essential for AWL. This research plays an important role in creating awareness and commitment for implementing a new algorithm base tactical planning system. With support we mean the support for the new system and the trust in the working of the new system. Support for the planning system should mainly be achieved during the development of the planning system.

A cultural change, within AWL, in which adhering to the tactical plan becomes a matter of course, is desirable. Section 2.4 describes that, currently, intermediary project deadlines or milestones are not always seen as strict deadline, but more as guidelines. Sound planning is impossible if not everything is done to meet intermediary deadlines. Periodical presentations should be held at various departments to explain the importance of adhering to the planning, to decrease disturbances and ultimately save costs. Emphasis should be placed on the advantages of structured planning with the help of an algorithm. Section 6.2 summarises these advantages.

The creation of awareness of the importance of planning should be done in parallel with the creation of support for the new planning system. Actors that directly work with the new system, such as the tactical planning function, IT, and the department schedulers, need to trust in a new algorithm based tactical planning system (Wallace et al., 2004). This trust is won by involving these actors closely in developing the new planning system. Involvement in development ensures that the actors provide relevant input and know how the system works. If users of the system do not trust the system, they will not utilise all functionalities of the system to its fullest. AWL should provide a systematic training and explanation of the system. Support of the managing board and department heads for the new planning system is important, and it is important that they actively express their support.

A guiding coalition should lead the implementation of the new planning system and should be held accountable for the progress. The guiding coalition should at least consist of the tactical planner, a board member, an experienced software engineer, and someone who is familiar with the working of planning algorithms. Also, a link should exist between the group and the AIM100-team, since the goals are in line with each other (as established in Section 2.1.2). The guiding coalition plays a key role in creating awareness and support. Section 5.7 describes an eight step plan, for developing commitment.

5.6 Costs And Challenges

So far, in this report we have mainly discussed advantages of a new algorithm based tactical planning system. This section discusses the costs and challenges associated with implementation.

Proper capacity planning software should be tailored to the needs of the company that uses the software. Estimating the cost for the implementation of a new algorithm based tactical planning system is difficult. Many variables play a role, such as the selected supplier, the comprehensiveness of the software package, and the intensity of the consultancy path. Because supplier selection is a task of AWL (which still needs to be performed), this section does not aim to exactly determine the cost of implementation, rather this section discusses the cost drivers. Suppose we stay at the lower end of our estimated savings interval of €636.000 and €1.060.000 on a yearly basis. We determine the payback period (in years) by:

$$\frac{\text{total implementation costs}}{(\text{€}636.000 - \text{yearly maintanence costs})}$$

In this formula the total implementation costs include the cost of the software package, the cost of consultancy activities by the supplier, the cost of cleaning up the data systems (Section 5.1), the cost of rearranging the tactical planning function (Section 5.2), the cost of training and presentations, and the cost of labour of AWL personnel involved in the implementation process. The yearly maintenance costs could include a service contract with the software supplier and potential cost of additional staff. AWL saves any cost involved with maintaining the old planning systems.

AWL staff should be included in implementation, which will be time-consuming for these actors. E.g., the tactical planner and the IT-specialist of AWL should be included in the project, which means that AWL should consider to reinforce these positions in order to make sure that their regular tasks are performed. AWL should also make sure that there is sufficient knowledge of planning algorithms within AWL, in order to be able to judge the supplier's work and maintain the system. As in any (software) implementation project, unforeseen problems are bound to occur. Either during the implementation phase or due to bugs in the system after implementation is finished (Wallace et al., 2004; Laudon & Laudon, 2007). AWL should be aware of these risks and room for contingencies should be allocated in the budget. AWL should also be aware that any sensitive company information might need to be shared with the software supplier and so proper agreements should be made as to how both parties should deal with different kinds of information. For an in-depth discussion of common risk factors in software projects we refer to Wallace et al. (2004).

5.7 Kotter's 8 Steps

In conclusion of this chapter on implementation, section describes how commitment for implementing the new tactical planning algorithm should be realised. This section specifies how the points mentioned in previous sections of this chapter should be realised. Kotter (1995) describes 8 steps for implementing change within an organisation. It is suitable to speak of organisational change when implementing a new algorithm based tactical planning system, since the tactical planning function is covering the whole organisation at AWL, many stakeholders are involved, and embedded habits need to be altered. Kotter's eight steps are listed below, with a short description of how we approach these steps.

Step 1: Establish a sense of urgency
Through talking to people from various departments at AWL it is easy to find out that there is already a widely supported feeling that something has to be done to improve the planning function. Everybody at AWL experiences at least some of the problems mentioned in Section 2.4, leading to unmet deadlines and a high variability in demand for various capacity groups. Urgency is felt because many people lose a considerable amount of time rescheduling or solving problems resulting from deviations from the plan or schedule. This research is also meant to establish a sense of urgency. Of the eight steps presented in this section, establishing a sense of urgency is the only step that is already completed.

Step 2: Create a guiding coalition
Early on, in the beginning phases of this project, a meeting has been planned to explain the goals and course of this project to a wide range of stakeholders, such as department managers, planners, and a member of the board. Some of the members of this group should be included in the coalition to create a wide support for implementing the new planning function. The guiding coalition should at least consist of the tactical planner, a board member, an experienced software engineer, and someone who is familiar with the working of the planning algorithm.

Step 3: Develop a vision and goals
A vision should be established to aid the change. The vision as defined for AIM 100 is also suitable for implementing the new, namely: to achieve better organisational performance and more output, without noteworthy expansion of capacity. Developing a vision and goals is the responsibility of the guiding coalition. The goals of the new planning system could for instance be as follows:

- Goal 1: 30% reduction of non-regular hours necessary (a yearly reduction of €636.000 at a total workload equal to that of 2012).
- Goal 2: Establishing confidence in the new planning method, in order to establish support for further automation and use of algorithms on the operational planning level.

Apart from the goals, that are directly related to the performance of the tactical planning algorithm, AWL should also attend to the recommendations in Section 6.3.

Step 4: Communicate the change vision
Progress of the project should be communicated on a regular basis by the guiding coalition to the whole organisation. This could, for instance, be done under the umbrella of AIM 100 initiatives. Also, as described in Section 5.2, a shift in responsibilities and communication lines should be achieved. The tactical planner should manage the project plans, rather than the project managers, and therefore the tactical planner should be provided with all necessary information via established methods, rather than by paying attention in corridors. This change of roles and communication lines should be communicated especially well to all personnel involved.

Step 5: Empower employees for broad-based action
New ideas and creativity should be encouraged within the guiding coalition and time and resources should be made available to personnel working on achieving the new tactical planning system. It is important to closely involve the future users of a new planning system in development, also (or especially) when the task of creating the new algorithm based tactical planning software is outsourced. This is important, not only to create trust in the system amongst future users, but also to make sure that all AWL specific requirements are included in the system.

Step 6: Generate short-term wins
Wins can only be generated when the new tactical planning system is in place, when the initial goals are met, these are short-term wins. These short-term wins should generate support for the next phases of implementing a new planning system based on algorithms. In order to be able to fully appreciate the gains, KPIs, such as expressed in Section 2.3, should be put in place and monitored.

Step 7: Consolidate gains and produce more change
Gains should be celebrated and used to create credibility. Increasing credibility of the guiding coalition should provide means to change systems, structures, and policies that do not fit the new planning method.

Step 8: Anchor new approaches in culture
Connections between the new initiatives and a better corporate performance should be articulated. Continuous improvement and maintenance of the planning function should be ensured.

Chapter 6: Implications & Recommendations

This chapter discusses the implications and recommendations resulting from this research. Section 6.1 discusses the scientific implications of implementing an algorithm based planning system. Section 6.2 the practical implications of implementing an algorithm based planning system. Sections 6.3 and 6.4 give recommendations for AWL to improve their planning.

6.1 Scientific Implications

The main scientific advancement of this research is an algorithm that takes into account non-regular capacity restrictions. This algorithm is an extension of the existing ICPA algorithm, hence its name Augmented ICPA. To our knowledge this is the first non LP-based heuristic that incorporates non-regular capacity restrictions. This restriction is important if a planning algorithm is to be useful in practice, such as exemplified by AWL in this research.

This research is a case study, in which algorithm based tactical multi-project planning is introduced to an ETO manufacturing organisation. The ifs and buts, as well as the potential benefits, of implementing these scientific planning algorithms in practice are exemplified in this research. The experiences from this research are helpful for scholars developing methods for tactical multi-project planning to keep an eye on what restrictions and considerations are important for such methods in practise. The experiences from this research are also helpful for other organisations that plan on refining their method of planning.

6.2 Practical Implications

The main practical implication of implementing an algorithm based planning system is that the organisation must be adjusted to the new system. From chapter 5 we learn that this adjustment entails two main things. First, awareness of the necessity and support for the new planning system should be created. Second, the organisational structure should fit the multi-project approach. In the case of AWL this means that the tactical planning function should expand and adopt more responsibilities (Section 5.2).

These adjustments do yield the following benefits of multi-project planning based on an algorithm:

- Savings in cost of non-regular capacity.
- Savings in time for familiarising non-regular personnel with operations.
- Savings in time spent on planning.
- More flexible planning; unforeseen events or delays are incorporated into a new plan quickly.
- Better and quicker insight into the effects of (possible) strategic and tactical decisions.
- Higher utilisation of regular capacity.

Costs and risks associated with the preparatory work, implementation, and maintenance of the system should be taken into account by AWL.

6.3 Direct Recommendations

This section gives recommendations that are directly related to a new algorithm based tactical planning system.

- AWL should employ a multi-project planning algorithm for tactical planning, to obtain the advantages of multi-project planning by an algorithm as defined in this report

- The communication lines and responsibilities of the tactical planning function and Project Management should be altered. In order to perform multi-project planning a central tactical planning function (the tactical planner) should be responsible for the project plan, also during the execution of projects. This renders that the tactical planning function plans from a multi-project (company-wide) view.

- We recommend that the KPIs (from Section 2.3) that are currently not recorded should be recorded. All KPIs should be actively used to assess the performance of the tactical planning function and the overall performance of AWL.

- The maximum number of non-regular hours should be determined for each capacity group and each time unit. It should be known exactly how much various types of non-regular capacity (e.g. overtime, temporary workers) costs.

6.4 Indirect Recommendations

This section gives recommendations, in addition to the recommendations that are directly related to a new algorithm based tactical planning system, based on perceived problems and other observations.

- Insight in the effects of employing inexperienced workers and temporary workers on the quality and the duration of work should be obtained. The general idea at AWL is that inexperienced or temporary workers work less efficiently than experienced workers. This effect should be taken into account when determining how much non-regular capacity for a certain period and capacity group is needed. There is also a difference in efficiency between various types of non-regular capacity: e.g., Czech workers, new temporary workers, temporary workers familiar with AWL.

- The operational scheduling method should be reassessed. We observe problems with the time it takes to schedule, the detail in which there has to be scheduled, and the multi-project overview that is missing in the scheduling software.

- Competences of employees should be inventoried in, e.g., a staff capability matrix. It is important to have an insight in the competences of employees company wide, to be able to plan properly, and to determine which competences have to be added to the workforce to avoid bottlenecks.

- The effects of the order acceptance policy should be assessed. From the capacity graphs of various departments, we see that the available capacity is often strongly exceeded. Flooding results in unrealistic deadlines, resulting in less time flexibility, and in overloaded resources. This, in turn, leads to less resource flexibility. Therefore, rough-cut planning to assist order acceptance decisions, by clearly defining the effects of a new project on the portfolio, is crucial.

- In order to make a robust plan (insensitive to disruptions during the course of projects), such as described in Section 2.7.3, AWL needs to map the uncertainty of activity workloads. These uncertainties are necessary to estimate the chance of exceeding capacity and thus the chance of delays. If uncertainties can be estimated, they can be incorporated in a planning algorithm with a (partial) objective function that aims to maximise a plans robustness.

- AWL should be able to estimate the value of free regular hours for capacity groups in a certain week. This way, the costs saved by an algorithm on non-regular capacity can be offset against the extra capacity that might be taken in the plan in comparison to another plan.

List Of Abbreviations

5S	Sorting, Setting in order of flow, Systematic cleaning, Standardising, and Sustaining.
AIM	AWL In Motion
al.	Alumni
ATW	Available To Work (window)
AWL	Aarding Weerstand Lassen (Grounding Resistance Welding)
BPR	Business Process Reengineering
BV	Besloten Vennootschap (Private Limited Liability Company)
CPM	Critical Path Method
CTO	Configure-To-Order
CZ	Czech Republic
e.g.	exempli gratia
ERP	Enterprise Resource Planning
ETO	Engineer-To-Order
FTE	Full-Time Employee
ICPA	Incremental Capacity Planning Algorithm
i.e.	id est
IT	Information Technology
IPC	Inter-Process Communication
JIT	Just-In-Time
KPI	Key Performance Indicator
LP	Linear Programming
MPE	Mechanical Pneumatic Electric
MRP	Material Resource Planning
MS	Microsoft
PLC	Programmable Logic Controller
RBT	Robot
RCCP	Rough-Cut Capacity Planning
RCPSP	Resource Constrained Project Scheduling Problem
R&D	Research & Development
RFQ	Request For Quotation
ROBCAD	Robotic Computer-Assisted Diagnosis
TPS	Toyota production System
WIP	Work In Process

Table 10: List of abbreviations

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Appendices

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2013

Appendix I: Capacity Group Characteristics

This appendix lists the various capacity groups distinguished at the tactical planning level at AWL, together with their current regular capacity, maximum non-regular capacity, cost of non-regular capacity, and the time period needed for arranging non-regular capacity. AWL distinguishes various capacity groups directly working on projects (*Table 11*). The values in *Table 11* are estimates by department heads or operational planners.

Group:	Regular capacity (hours per week):	Max. non-regular (hours per week):	Cost of non-regular capacity (cost per hour)	Time span in which non-regular capacity can be arranged
Electric Wiring	400	400	34€ to 52€	1 day
Engineering	160	40	±40€	±4 weeks
Engineering Control	120	-	-	-
Engineering E-Plan	280	80	±55€	1 to 2 weeks
Engineering RobCAD	160	240	26€	±1 month
Jig Assembly	440	440	±45€	±2 weeks
Logistic Engineering	156	24	±56€	±1 week
Measure Fixture	112	120	±100€	±2 weeks
Mechanical Assembly	520	520	34€ to 52€	1 day
Mechanical Engineering	216	80	±45€	1 to 4 weeks
Parts Production & Purchase	476	476	±45€	1 to 4 weeks
PLC Programming	336	120	57€ to 65€	3 to 8 weeks
Process Quality	220	40	57€ to 65€	-
Project Management	592	-	-	-
RBT Programming	352	160	65€ to 80€	4 to 14 weeks
RBT Welding	160	120	60€ to 70€	2 to 3 weeks
Weld Quality Lab	80	160	34€ to 52€	±1 week

Table 11: Capacity groups

Some notes have to be made:

- The maximum non-regular capacity of Jig Assembly, Electric Wiring, Parts Production & Purchase, and Mechanical Engineering is unknown; fact is that if high levels of non-regular force is used that are not familiar with AWL, fixed personnel has to be used to guide newcomers. So, there should be a theoretic maximum to the possible amount of non-regular. Therefore, we have estimated the max. Non-regular capacity at equal to the regular capacity.
- Non-regular personnel for Electric Wiring and Mechanical Engineering can be arranged in one day. However, to arrange non-regular personnel that is familiar with AWL, for these capacity groups, takes 1 to 2 weeks. Familiar non-regular personnel can start working immediately and the quality of their work is more certain.
- For PLC & RBT Programming, the regular capacity has been reduced by 20% of the total availability, because on average 20% is lost to Service & Maintenance activities.
- For Project Management, usually no non-regular hours are used. Only in the case of very specific parts of projects, it might be an option to use non-regular capacity.
- The numbers for Engineering RobCAD are based on their ability to outsource activities to India. The department estimates that non-regular capacity works 15%.
- The non-regular capacity in this figure is the external non-regular capacity; overtime (internal non-regular capacity) is not included.

Appendix II: KPI formulas

This appendix gives formulas to illustrate how the KPIs described in Section 2.3 should be measured. An explanation of the symbols used in the formulas follows:

N activities $A_1, ..., A_N$, need to be planned on K resources $R_1, ..., R_K$. The considered time horizon is divided in T time-buckets $t = 1, ..., T$. Each resource R_k has Q_{kt} capacity available in time-bucket t. Activity A_a requires q_{ak} hours of processing time on resource R_k. In any time-bucket at most $1/p_a$ of an activity A_a can be executed, thus p_a is the minimum duration of activity A_a. Activity A_a's release date is r_a and its deadline is d_a. h_a the actual finish date of activity A_a.

In each time-bucket t, x_{at} indicates a proportion of the workload of activity A_a is performed. The set P_a contains the predecessors of activity A_a, so each activity in P_a must be finished before A_a can start.

Overtime, temporary workers, and outsourcing are examples of types of non-regular capacity. We denote these various types by $g=1, \ldots, G$. We denote the cost of using one hour of non-regular capacity for capacity group k in time-bucket t of type g by c_{ktg}. f_{ktg} is the number of non-regular hours for capacity group k in time-bucket t that is of type g.

There are O milestones $M_1, ..., M_O$. Milestone M_m has a deadline d_m. d_m is defined by the latest due date of an activity in the set P_m. P_m contains all activities that have to be finished before a milestone is completed. h_m is the actual finish date of the last finished activity in the set P_m. If $h_m > d_m$, then indicator function $I_{hm>dm}=1$, else $I_{hm>dm}=0$. If milestone M_m is the final milestone in a project (customer/project due date), then indicator function $J_m=1$, else $J_m=0$. e_m is defined as the original due date of a milestone, if during the project the due date of a project is altered (revised), then d_m changes to a new value and e_m stays the same. If $d_m > e_m$, then indicator function $L_{dm>em}=1$, else $L_{dm>em}=0$.

$s_{a\alpha}$ is the delay of activity a caused by preceding activity α. $s_{a\alpha}$ is a subjective measure which is estimated by the department that handles activity A_a. The sum of all $s_{a\alpha}$'s for a certain a is not necessarily 1, because delays can also be caused by other causes then poor quality of preceding activities.

i_{at} is the budgeted (expected beforehand) expenses during time-unit t necessary to complete activity a, whereas j_{at} is the actual expenses made time-unit t to complete activity a.

The formulas represent the overall average performance of the full system for the considered KPIs. These formulas can be easily adapted to represent the performance of, for instance, one capacity group at a time.

- **KPI 1 & 2**

We measure the extent to which milestones are met can be measured by the number of unmet milestones (*KPI 1*) or the sum of time units by which milestones are not met (*KPI 2*).

$$\text{KPI1} : \sum_{m=1}^{O} I_{h_m > d_m}$$

$$\text{KPI2} : \sum_{m=1}^{O} max(0, h_m - d_m)$$

- **KPI 1* & 2***

We measure the extent to which customer deadlines are met can be measured by the number of deadlines not met (*KPI 1**) or the sum of time units by which deadlines are not met (*KPI 2**).

$$\text{KPI1}^* : \sum_{m=1}^{O} (J_m I_{h_m > d_m})$$

$$\text{KPI2}^* : \sum_{m=1}^{O} max(0, (h_m - d_m)J_m)$$

- **KPI 3 & 4**

The number of revisions of a tactical plan can be measured by how many milestones are postponed (*KPI 3*) and by how much these milestones are postponed (*KPI 4*). If the postponement of a milestone early in a project causes consecutive milestones to be postponed, we measure the total number of postponed milestones.

$$\text{KPI3} : \sum_{m=1}^{O} L_{d_m > e_m}$$

$$\text{KPI4} : \sum_{m=1}^{O} max(0, d_m - e_m)$$

- **KPI 5**

Various non-regular capacity types per capacity group can be distinguished (e.g. overtime, capacity from CZ, temporary workers from company A, temporary workers from company B, etc.). These capacity types imply different costs. The total cost of non-regular capacity can be measured by the sum of cost of non-regular capacity used.

$$\text{KPI5} : \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{\mathrm{g}=1}^{\mathrm{G}} (f_{ktg}\, c_{ktg})$$

- **KPI 6**

The degree of fluctuation of capacity demand can be measured by either the average deviation of needed capacity from the average capacity demand (*KPI 6A)*, or the deviation for this week's capacity demand from last week's capacity demand (*KPI 6B*).

$$\text{KPI6A:} \sum_{k=1}^{K} \sum_{t=1}^{T} \left| \left(\sum_{a=1}^{N} q_{ak} x_{at} \right) - \frac{\sum_{a'=1}^{N} q_{a'k}}{T} \right|$$

$$\text{KPI6B:} \sum_{k=1}^{K} \sum_{t=2}^{T} \left| \sum_{a=1}^{N} (q_{ak} x_{at} - q_{ak} x_{a,t-1}) \right|$$

- **KPI 7**

The quality of an activity is measured by how much delay of successive activities is caused by mistakes of the activity, recall that $s_{a\alpha}$ is a subjective measure which is estimated by the department that handles activity A_a. If we look at this formula for one value of α, instead of a summation over all α's, then we have a subjective measure of the quality produced by department α.

$$\text{KPI7:} \sum_{\alpha=1}^{A} \sum_{a=1}^{A} s_{a\alpha}$$

- **KPI 8 & 9**

The difference between budgeted expenses and actual expenses can be measured by the sum of the difference between total budget and actual total expenditure (*KPI 8*) or the sum of the absolute difference between budget and expenditure per time unit (*KPI 9*). *KPI 9* also considers it a problem if actual expenditure is less than budgeted, because this means the budget was of. Excess money allocated to a project budget could have been spent elsewhere.

$$\text{KPI8:} \sum_{\mathrm{t}=1}^{\mathrm{T}} \sum_{a=1}^{A} (i_{at} - j_{at})$$

$$\text{KPI9:} \sum_{\mathrm{t}=1}^{\mathrm{T}} \sum_{a=1}^{A} |i_{at} - j_{at}|$$

- **KPI 10**

The time spent on operational and tactical planning activities is a summation of the time spend on planning activities for the considered time period. (no formula needed)

- **KPI 11**

The number of changes in a project team is the number of times, in the considered time period, that the formation of a project team changes. The project team consists of a Salesman, Project Leader, Project Coordinator, Logistic Engineer, ROBCAD Engineer, Project Engineer, PLC Technician, Robot Technician, and a Head Mechanic. (no formula needed)

Appendix III: KPIs And Current Performance

This appendix describes if KPIs are currently measured at AWL and, if so, how they are performing in terms of the KPI.

KPI 1 & KPI 2

KPI 1 & KPI 2 both relate to the measurement of how often milestones are not met. This question is an important element of this research as Section 1.2 describes it as the main problem. Currently, however, AWL does not keep track of the number of milestones not met. Keeping track of this KPI would be crucial to measure the performance of the tactical planning function and it would also show which activities or departments do not meet their milestones frequently. This would also be a good starting point for a more thorough investigation of why milestones are not met.

KPI 1 & KPI 2**

*KPI 1** & *KPI 2** both relate to the measurement of how often customer deadlines are not met. The planned and actual finish dates of projects are mostly not well recorded. It is therefore not possible to give the current performance of AWL on these indicators.

KPI 3 & KPI 4

KPI 3 & *KPI 4* both relate to the measurement of how often milestones are postponed. The project leader can make a revision of the project plan, together with the tactical planner, if a milestone needs to be postponed by one week or more. AWL does not record the number of revisions currently done per time unit. AWL, however, knows what the current version of the project plans currently in execution is. There is, however, no insight in how many revisions are done per month, or how many revisions have been performed in the past for finished projects. An estimate is 4 to 8 revisions of project plan are made on average per project. The average duration of a project is 8.6 months and there are about 26 projects worked on simultaneously. This means we estimate that AWL has (6/8.6) *29 ≈ 20 revisions of project plans per month on average (based on figures from 2012).

KPI 5

KPI 5 relates to the cost of non-regular capacity. This data is recorded and can be retrieved from the ERP-system. This measure is, however, not yet used as a KPI for tactical planning performance or AWL as a whole. From January 2011 to July 2013, AWL has spend 47 thousand hours on overtime and 117 thousand hours on external non-regular capacity, on a total of 1.01 million hours worked. So, approximately 15% of the hours produced was filled by non-regular capacity. From January 2011 to July 2013, the cost of overtime was 5.5 million euro (of which 5.3 spend by departments involved in direct project activities).

KPI 6

KPI 6 relates to the average deviation of needed capacity from the average capacity demand, i.e. how levelled demand is. This is not a performance indicator that is currently measured by AWL, but it can be retrieved from historic data on capacity at the various resource groups. For this indicator we have to decide on the time unit to be considered; this can be, for instance, days or weeks. Both the daily and the weekly point of view provide information about the performance of the tactical planning function. Furthermore, for this indicator we have to decide on the length of times pan T to be considered and if we look at the future or at the past.

For instance, we can look at the performance of Jig Assembly on *KPI 6*, during the first half of 2013, looking at the deviation per week. *Table 12* gives the hours used by the jig assembly department per week and the deviation from the average over period T. The average deviation is the performance of jig assembly with set parameters on *KPI 6*, so: on average there is a 124.2 hours deviation per week from the average demand for hours.

	Hours	Deviation from period average		Hours	Deviation from period average
Week 1	164	297.5	Week 14	679	217.5
Week 2	257	204.5	Week 15	644	182.5
Week 3	189	272.5	Week 16	709	247.5
Week 4	453	8.5	Week 17	473	11.5
Week 5	365	96.5	Week 18	364	97.5
Week 6	408	53.5	Week 19	100	361.5
Week 7	499	37.5	Week 20	419	42.5
Week 8	483	21.5	Week 21	454	7.5
Week 9	530	68.5	Week 22	686	224.5
Week 10	402	59.5	Week 23	385	76.5
Week 11	600	138.5	Week 24	425	36.5
Week 12	547	85.5	Week 25	536	74.5
Week 13	531	69.5	Week 26	698	236.5
			Average	461.5	124.2

Table 12: Jig Assembly performance on KPI 6

KPI 7

KPI 7 relates to how much delay of an activity is caused by mistakes of preceding activities, which is a measure for the quality of the work performed during an activity. Insight in the performance of various activities over several projects, would give an indication of where processes need to be improved to avoid mistakes. This indicator is currently not measured.

KPI 8 & 9

KPI 8 and *KPI 9* relate to the degree to which budgets are deviating from actual budgets. *KPI 8* measures this on the level of the whole project, *KPI 9* measures this on the level of an activity over a certain time unit (for instance a week). From data out from the ERP-system of AWL, these measurements can be derived for projects finished in 2011 and 2012.

To give an indication of the deviation of the workload estimated at the start of the project from the actual duration, *Figure 42* gives the sum of estimated hours and actual hours over 2011 and 2012 for each department separately.

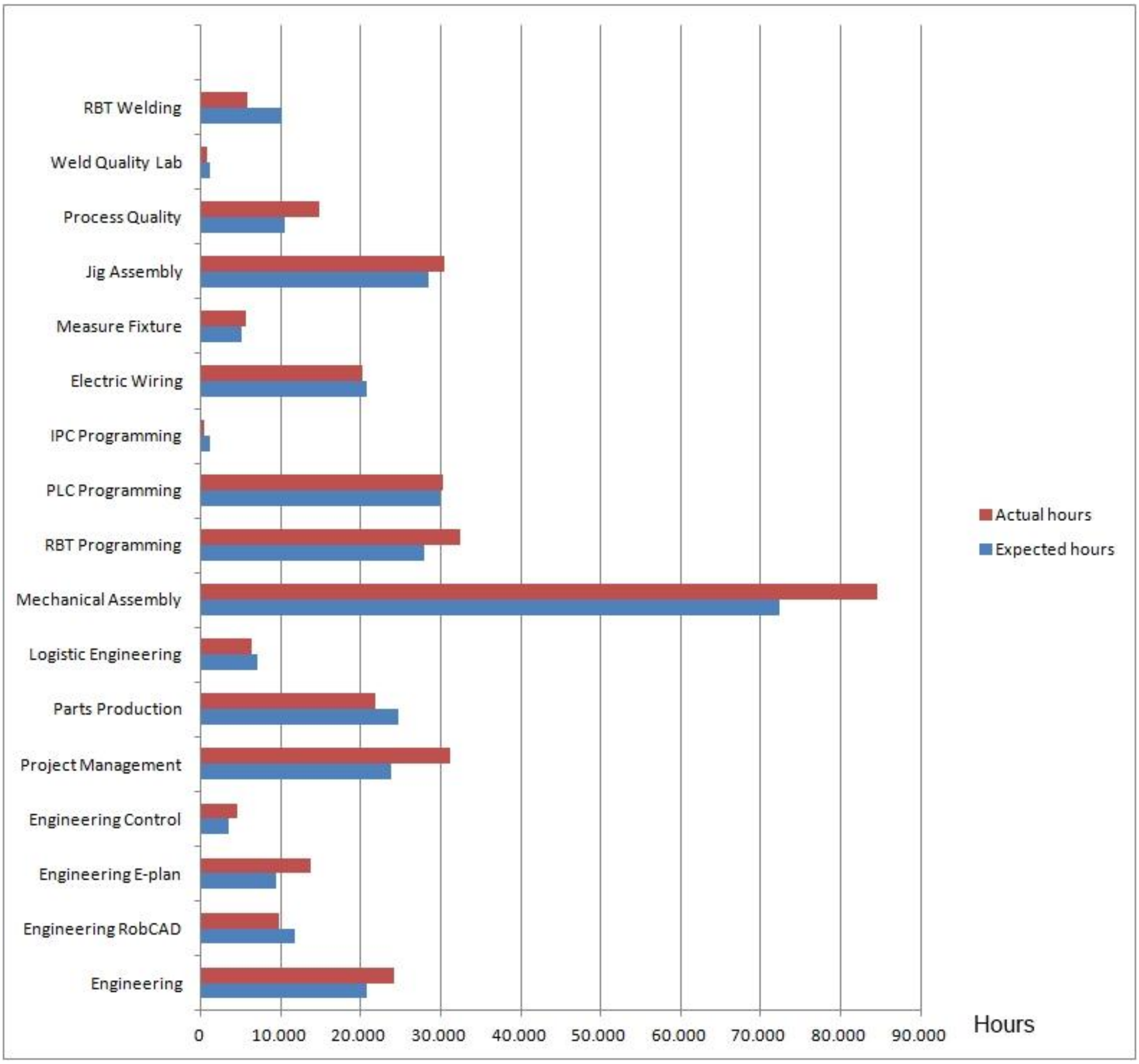

Figure 42: Deviation of hours per department

Over all departments and two years, there is a total of 30.000 hours used more than expected. *Figure 43* shows the sum of the absolute deviations per department.

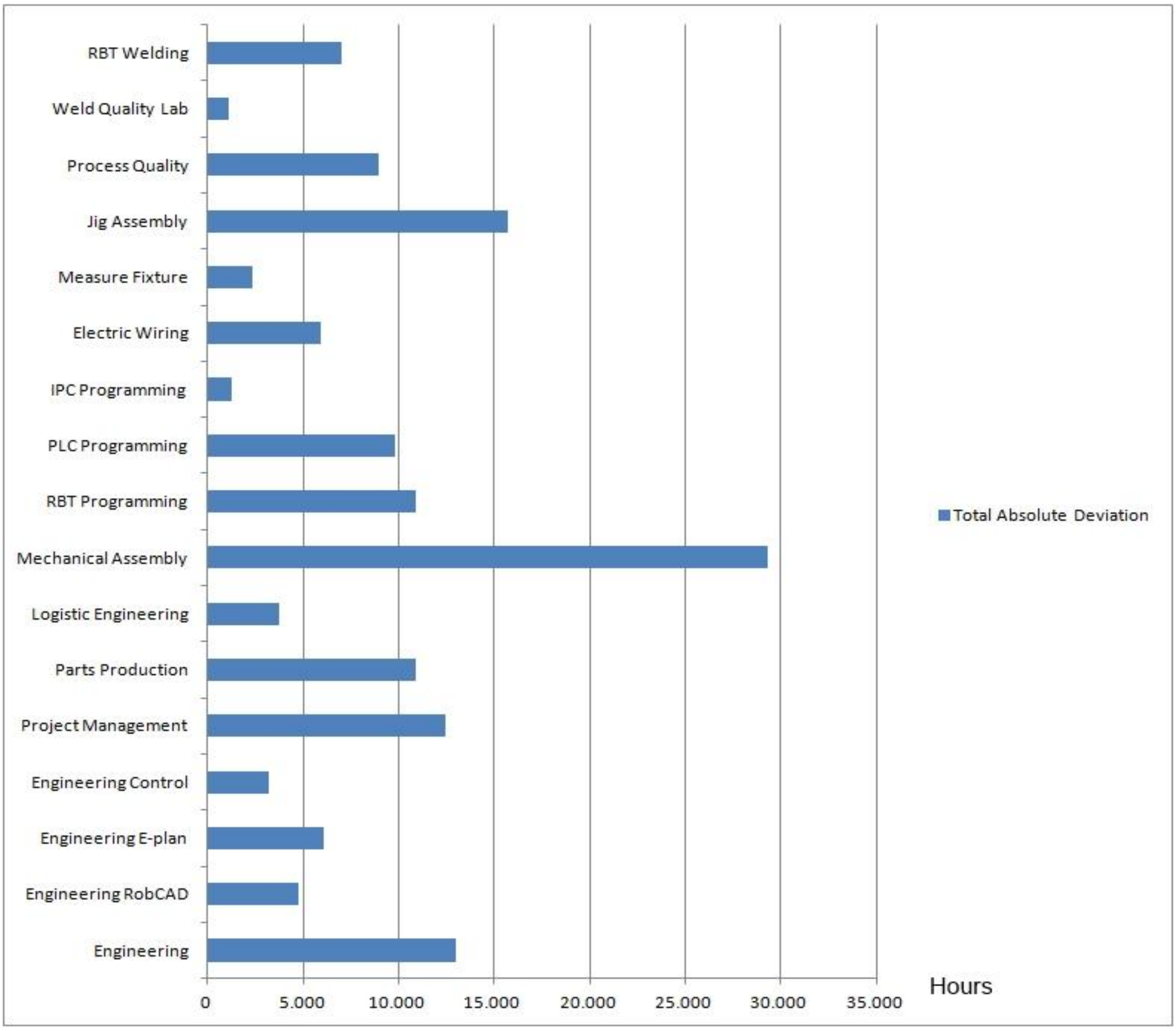

Figure 43: Total absolute deviation of expected and actual activity duration per department

From *Figure 43* we conclude that improving the estimation of the hours needed for Mechanical Assembly, Jig Assembly, and Engineering would reduce the uncertainty within a project. It is difficult, however, to determine if the deviations are inherent to ETO, or that the estimation process at the Calculation department needs to improve, or that deviations are caused by delays because of unforeseen setbacks.

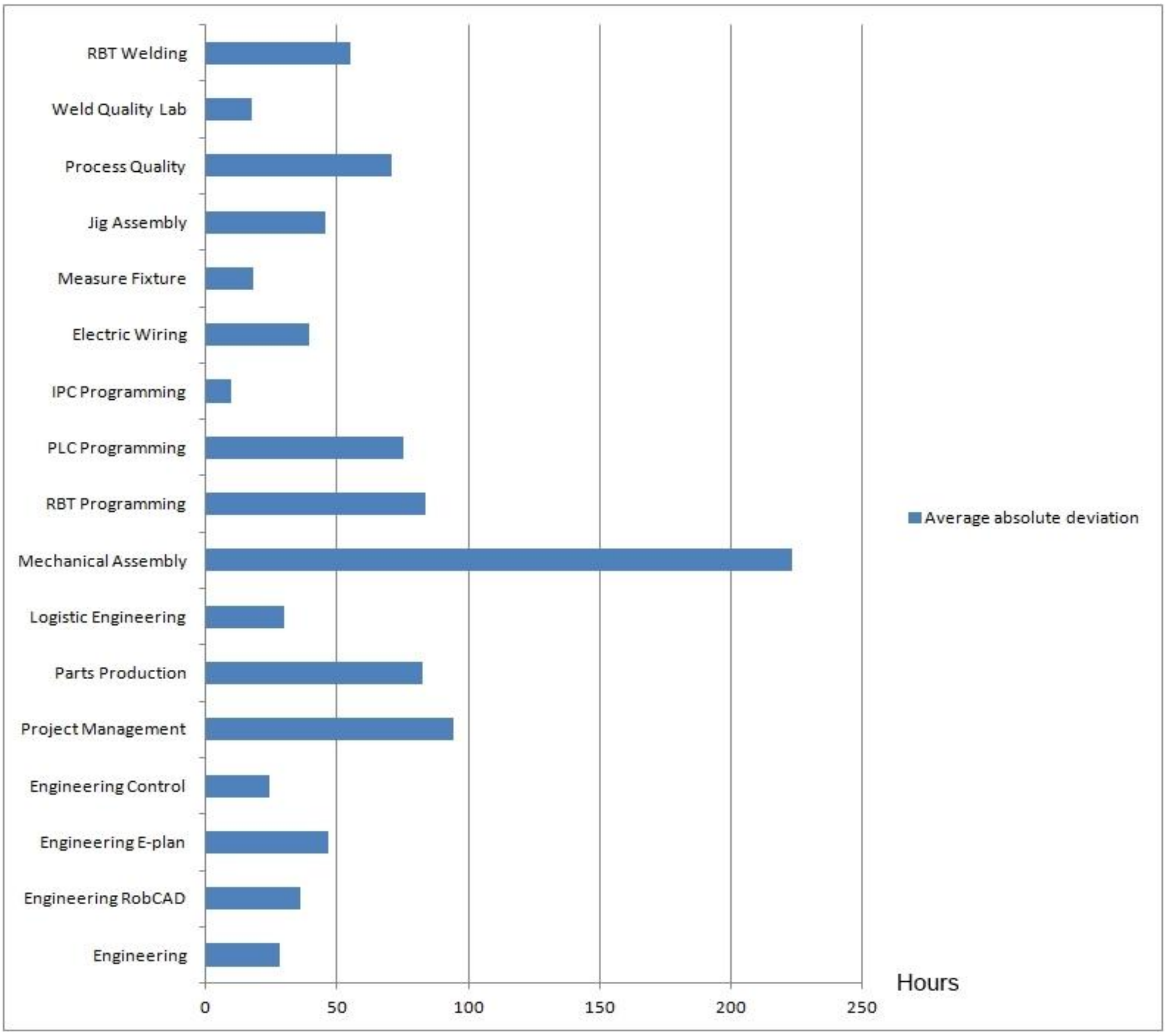

Figure 44: Average absolute deviation of expected and actual activity duration per department

Then we divide that total absolute deviation per department by the number of activities considered, so we find the average absolute deviation of the estimated and the actual duration of an activity performed at a certain department (*Figure 44*). We conclude that the largest uncertainty in a project's process is found at the mechanical assembly department, if we define uncertainty as the deviation of the expected hours to work on an activity and the actual number of hours worked on an activity.

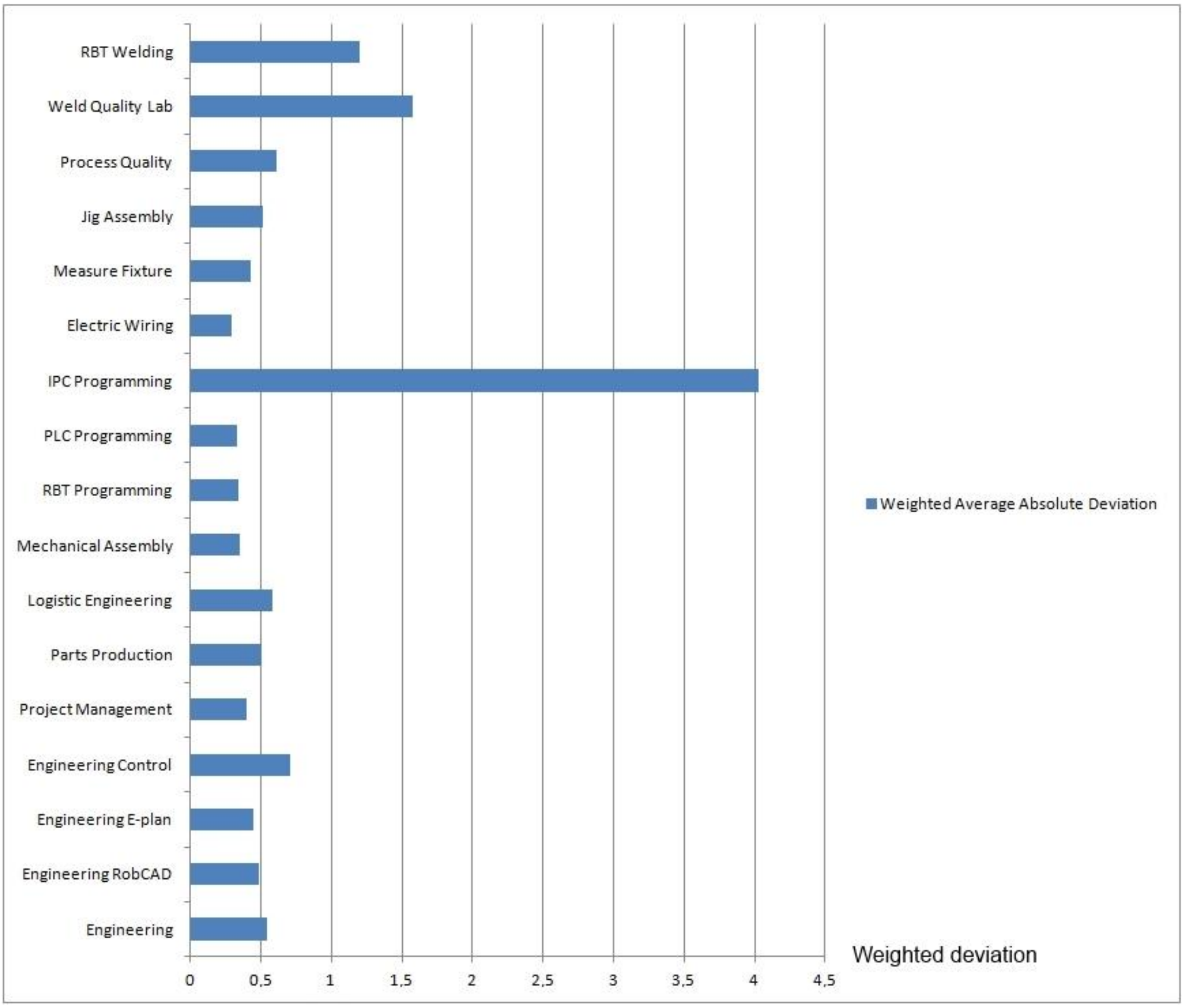

Figure 45: Weighted average absolute deviation of expected and actual activity duration per department

If we then divide the average absolute deviation by the average duration, we get a weighted average absolute deviation of expected and actual activity duration, which gives a more fair comparison of the level of deviation between activities (*Figure 45*). From this we learn that estimations for the duration of IPC Programming activities are less reliable then estimates of durations for other activities. The total effect of the less reliable estimates for IPC Programming on the planning process whole are relatively small, due to the short average duration of the activity.

KPI 10

KPI 10 relates to the time spent on operational and tactical planning activities. This is currently not recorded. Some rough estimates are available. The operational planner of the assembly department estimates that he spends 15 to 20 hours a week planning (including alterations etc.). The jig assembly planner estimates that he spends 2 hours a week on operational planning activities.

KPI 11

KPI 11 relates to the number of changes that are made in the composition of a project team. This is currently not measured.

Appendix IV: ICPA Heuristic Example

This appendix illustrates the ICPA heuristic for the example in Section 2.6.2 and compares its performance to the performance of the schedule found in *Figure 16* an *Figure 17*. First we have to determine the due dates for all activities by subtracting from the project due date the minimum processing times of succeeding activities. In the example, the minimum processing times are durations given in *Table 3*. *Table 13* gives the due dates of the activity j (d_j), the minimum duration of the activity j (p_j), and the total number of worker hours needed for capacity group k for the activity j (q_{jk}). The minimum duration of an activity is defined by dividing the total activity work load by the maximum number of workers that can work on a activity during a time unit.

	d_j	min. p_j	q_{jk}		d_j	min. p_j	q_{jk}
E1	3	2	2	E3	4	2	2
WP1	4	1	2	WP3	6	2	4
A1	10	6	36	A3	11	5	20
P1	14	4	4	P3	15	4	8
T1	15	1	1	T3	16	1	1

	d_j	p_j	q_{jk}		d_j	p_j	q_{jk}
E2	6	2	2	E4	-	-	-
WP2	7	1	2	WP4	7	1	2
A2	11	4	16	A4	11	5	20
P2	14	3	3	P4	15	4	4
T2	15	1	1	T4	16	1	1

Table 13: Activity characteristics

The ICPA heuristic plans activities in order from low d_j to high d_j. So we start by planning activity E1 (engineering for project 1). The min. duration of activity E1 is 2 weeks; this means a requires $q_{E1,E}/p_{E1}$ = 1 engineer per week. Since, we have not planned anything yet, the regular capacity constraints of the engineering department are not breached if we plan activity E1 as early as possible (see *Figure 46*).

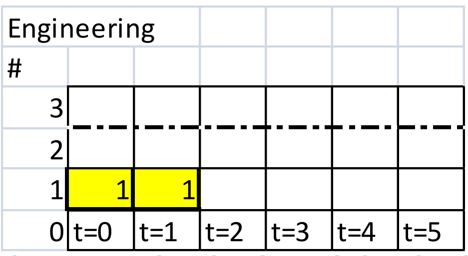

Figure 46: Engineering demand after planning E1

We can now choose to plan either activity WP1 and E3 as both activity due dates are the lowest. We choose to first plan WP1, the earliest time at which WP1 can start is t=2, because that is when all its predecessors (E1) are finished. We plan as much of the activity as early as possible. This means we plan the full activity from t=2 to t=3 (see *Figure 47*).

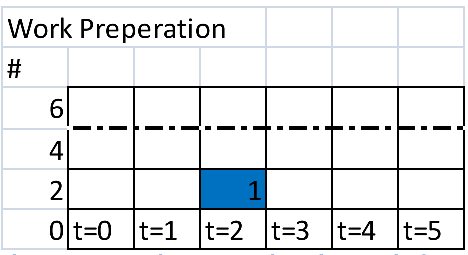

Figure 47: Work Preparation demand after planning WP1

We continue planning activities this way, until we first encounter a breach of the regular capacity of a capacity group if we plan an activity from its earliest allowed starting point. This is when we plan activity E2. If we plan the maximum of the activity as early as possible we need $q_{E2,E}/p_{E2} = 1$ engineer per week for t=0 to t=2. However, if we look at *Figure 48*, we see that we have already fully used the regular capacity of the engineering department for weeks t=0 to t=2. However, since the deadline for activity E2 is t=6, we are allowed to start the activity somewhat later. The earliest time to start the activity, without breaching regular capacity constraints, is at t=2 (see *Figure 48*).

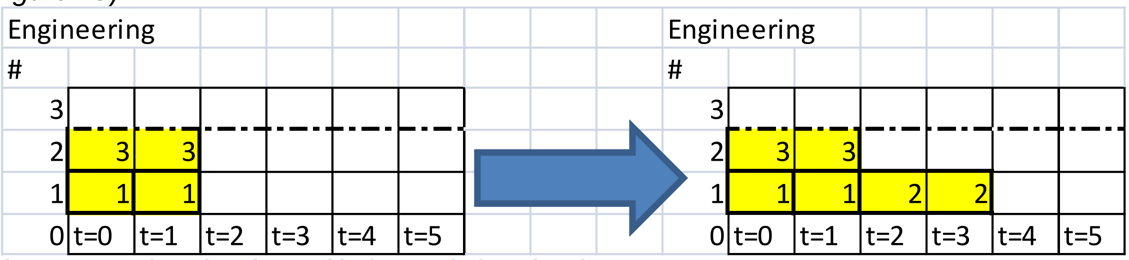

Figure 48: Engineering demand before and after planning E2

When we continue to plan the activities this way, we first encounter a breach of constraints when trying to plan as much of activity A3 as soon as possible. Activity A3 is allowed to start at t=4. . If we plan the maximum of the activity as early as possible we need $q_{A3,A}/p_{A3} = 4$ workers per week for t=4 to t=9. However, from *Figure 49* we see that from t=5 to t=9 there are no more workers available in regular capacity. Since d_{A3} =11, we can plan some of activity A3 in week t=3 to t=4 and in weeks from t=9 to t=11. However, we can plan a maximum workload equal to 4 workers per week. This means that we still have to plan workload equal to 8 worker weeks from t=5 to t=9.We can use a maximum of four workers for the activity during one time unit, so if we plan as early as possible, we need four extra workers (non-regular) on both t=5 and t=6 (*Figure 50*).

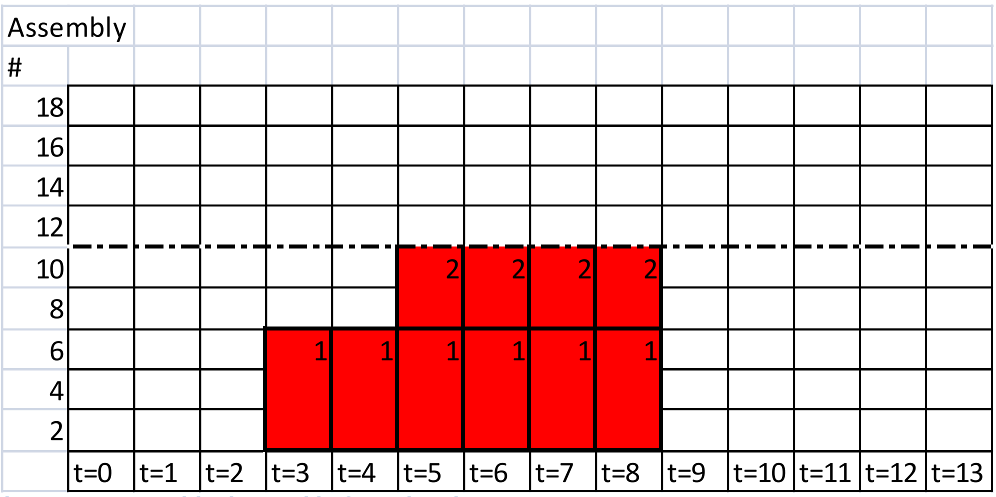

Figure 49: Assembly demand before planning A3

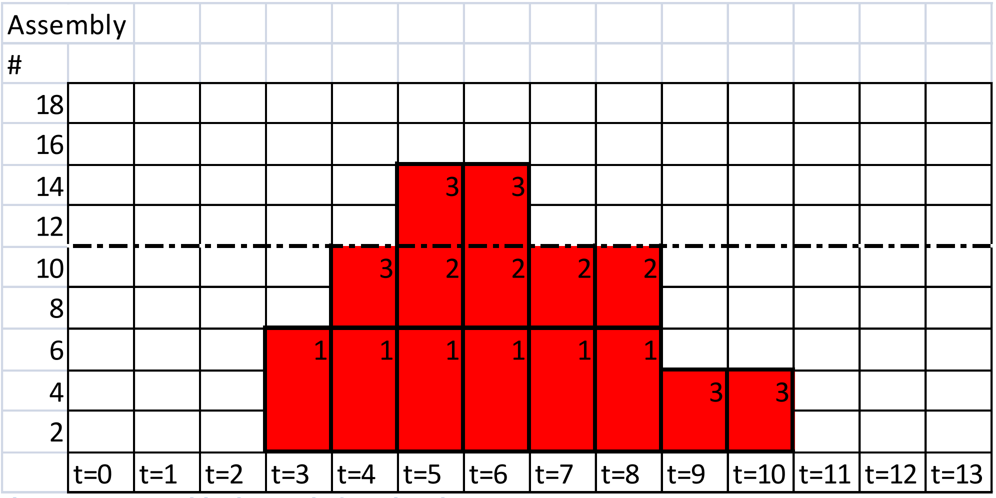

Figure 50: Assembly demand after planning A3

If we continue to plan using the ICPA heuristic, *Figure 51* displays the resulting plan.

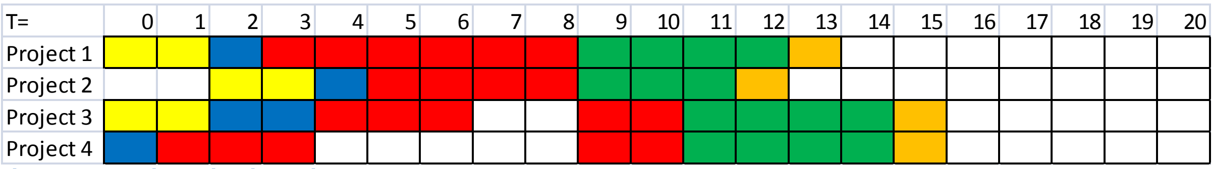

Figure 51: Project plan based on ICPA

Although, the project plan in *Figure 51* might look less intuitive than the project plans in *Figure 16* and *Figure 17*, the ICPA project plan performs better in terms of hours of non-regular capacity needed. The plan resulting from the ICPA needs 8*40 hours extra Assembly capacity (*Figure 50*) and 3*40 hours extra Programming capacity. *Table 14* gives the needed non-regular capacity for the other project plans.

	Forward Scheduling	Backward Scheduling	ICPA
Engineering	80	40	0
Work Preparation	40	0	0
Assembly	960	1200	320
Programming	80	240	120
Testing	80	80	0
Total hours	1240	1560	440

Table 14: Comparison of several planning approaches on use of non-regular capacity

We see that employing a simple heuristic can reduce the need for non-regular capacity in comparison to forward or backward scheduling. Note that with the reduction of non-regular capacity needed, the fluctuation in demand per department is also reduced. More advanced algorithms are available which can yield better results, especially for larger problem instances (e.g., more resource groups and more projects). The cost of non-regular capacity for various capacity groups can also be incorporated. Furthermore, when an algorithm is automated, the time spend on planning can be drastically reduced.

Appendix V: Applications Used For Explanation And Calculations

This appendix discusses the two prototype applications that were made to support the message of this research that algorithms should be employed for tactical planning at AWL. Furthermore, this appendix briefly introduces a third application in which the calculations for the LP-Heuristic are performed.

The first prototype application (Application I) can employ the ICPA and Augmented ICPA for problem instances that are a simplification of reality, in that we only distinguish five sequential steps and a maximum number of six projects. The relevant data of the problem instance is entered in the screen depicted in *Figure 52*. The non-regular capacity of resources can be inserted at the bottom of the screen. Figure 53 depicts the results screen of Application I, in which the effects on the capacity demand of several departments is shown, together with the non-regular hours needed in the plan resulting from (Augmented) ICPA and the associated cost of non-regular capacity. Application I is used for the example in Section 2.5.3.

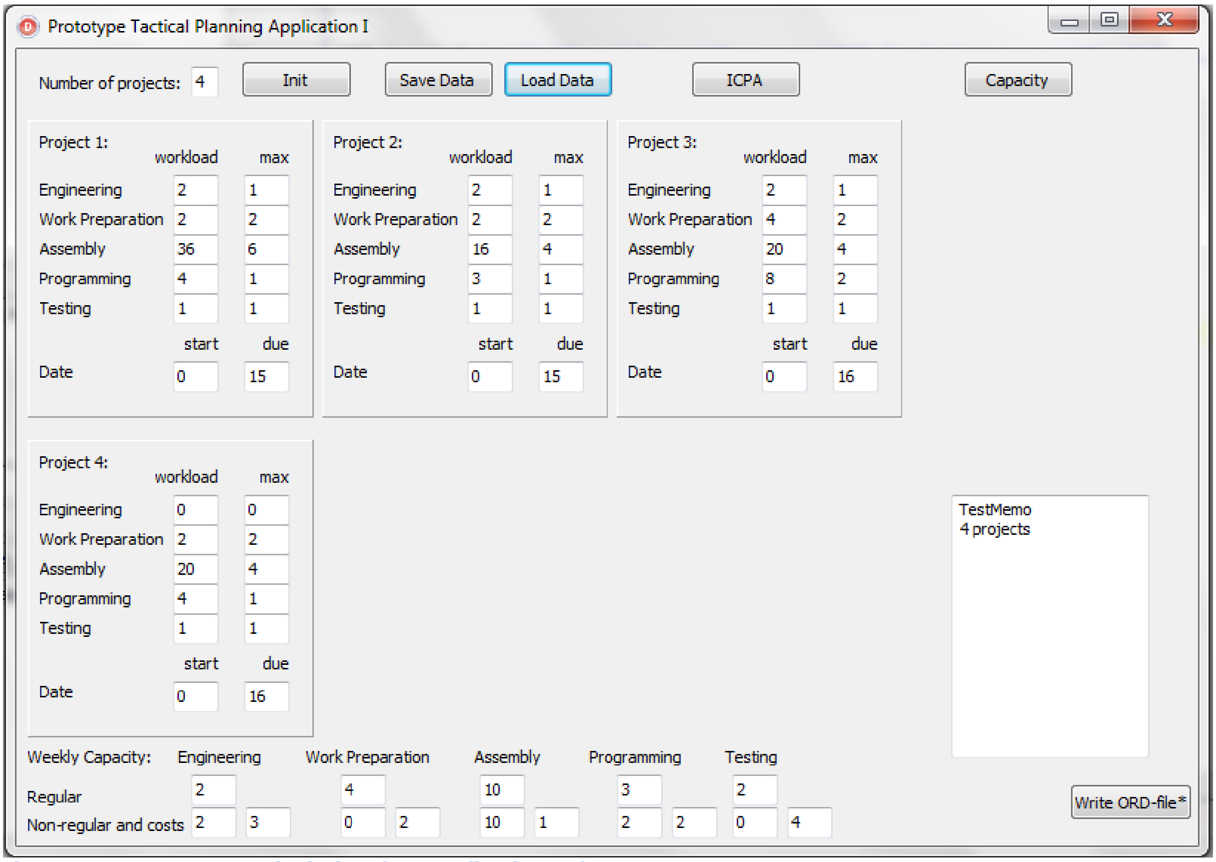

Figure 52: Prototype Tactical Planning Application I, data entry screen

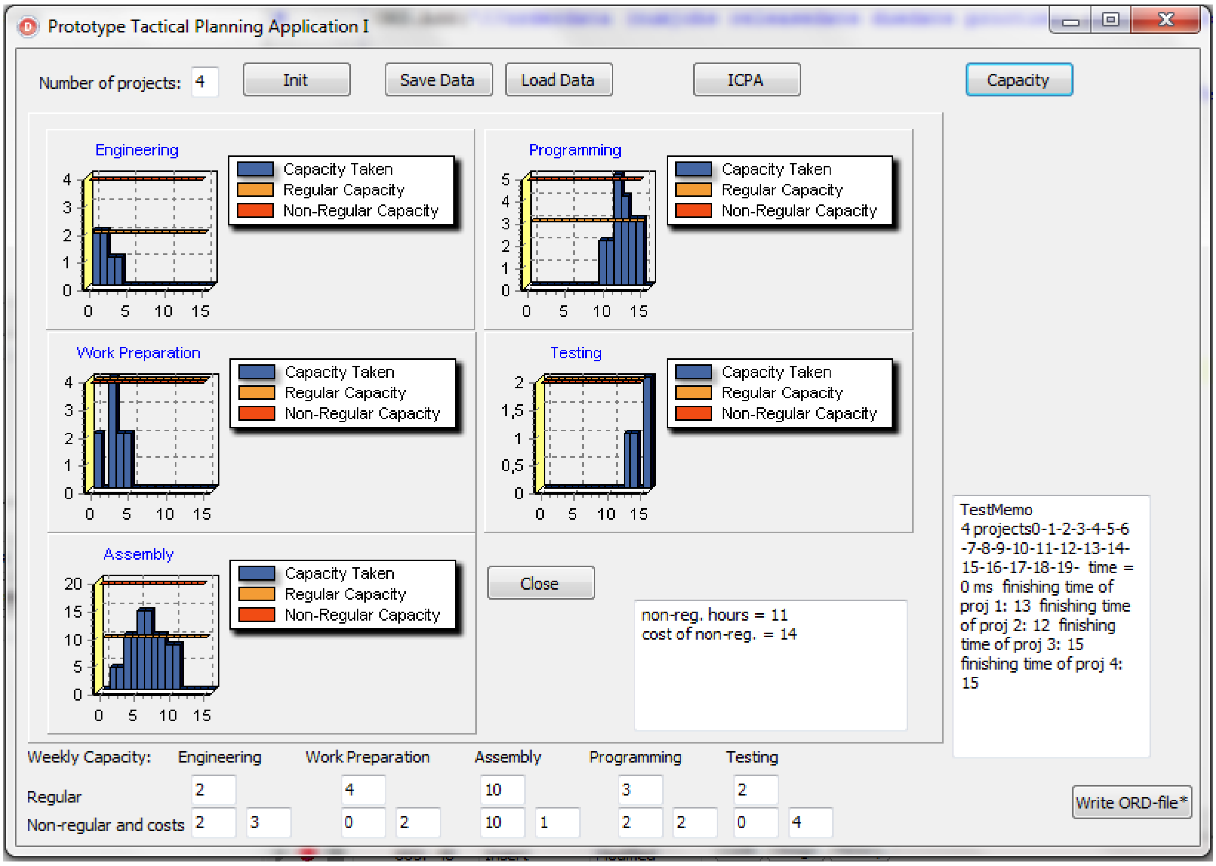

Figure 53: Prototype Tactical Planning Application I, results screen

The second prototype application (Application II) is used for determining the performance of the current tactical plan, ICPA, and Augmented ICPA for the experiments in Chapter 4. The relevant data was manually inserted in the code of the application. The application shows the effects of the total tactical plan and of individual project plans on all capacity groups (*Figure 54*). Furthermore, the performance on the other measures considered in Chapter 4 are included. The non-regular capacity of resources can be inserted at the left-bottom of the screen. The application can also translate the problem instance data in the code of the application and resulting from calculations into an ORD-file and a COL-file, so that this data can be used in Application III.

Figure 54: Tactical Planning Application II

The third application (Application III) that is used in this research is an application made by Erwin Hans for his PhD research (Hans, 2001), and for further experimentation with the RCCP. This application performs the calculations for the LP-Heuristic and the average slack of problem instances. First all relevant data is loaded into the program via an ORD-file and a COL-file that were produced by Application II. Then the LP-Heuristic can start and the objective values resulting from the iterations of the LP-Heuristic are shown. A report of the resulting solution can be assembled by pressing the “Save solution”-button. We have added the minimise cost objective and the various performance measures considered in this report to this application. *Figure 55* depicts a screenshot of Application III.

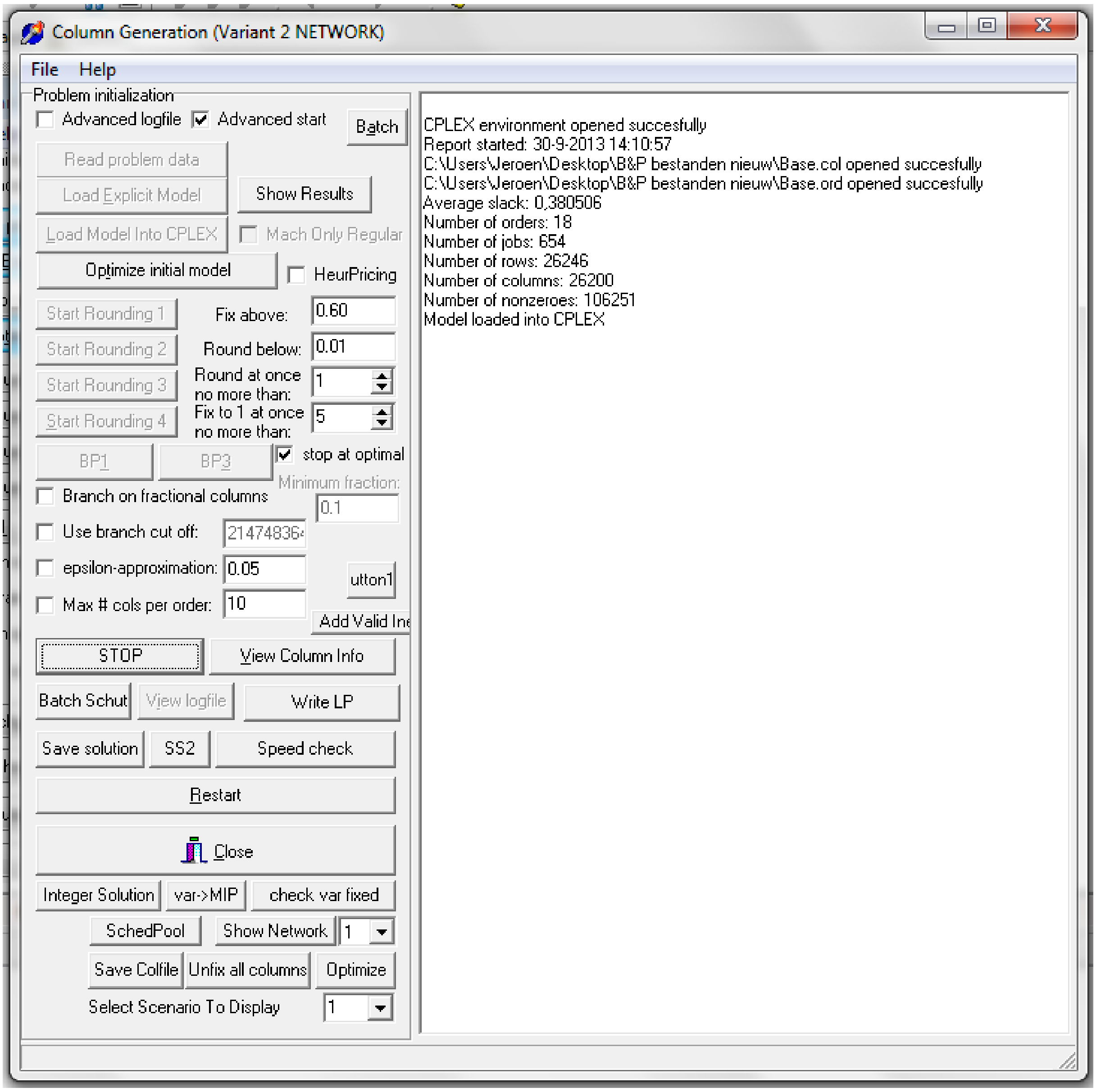

Figure 55: Application III used for determining the performance of the LP-Heuristic

Appendix VI: Augmented ICPA Schematic Figure

This appendix schematically displays how Augmented ICPA works. We define slack as the difference between the minimum duration of the activity and the actual duration of the activity.

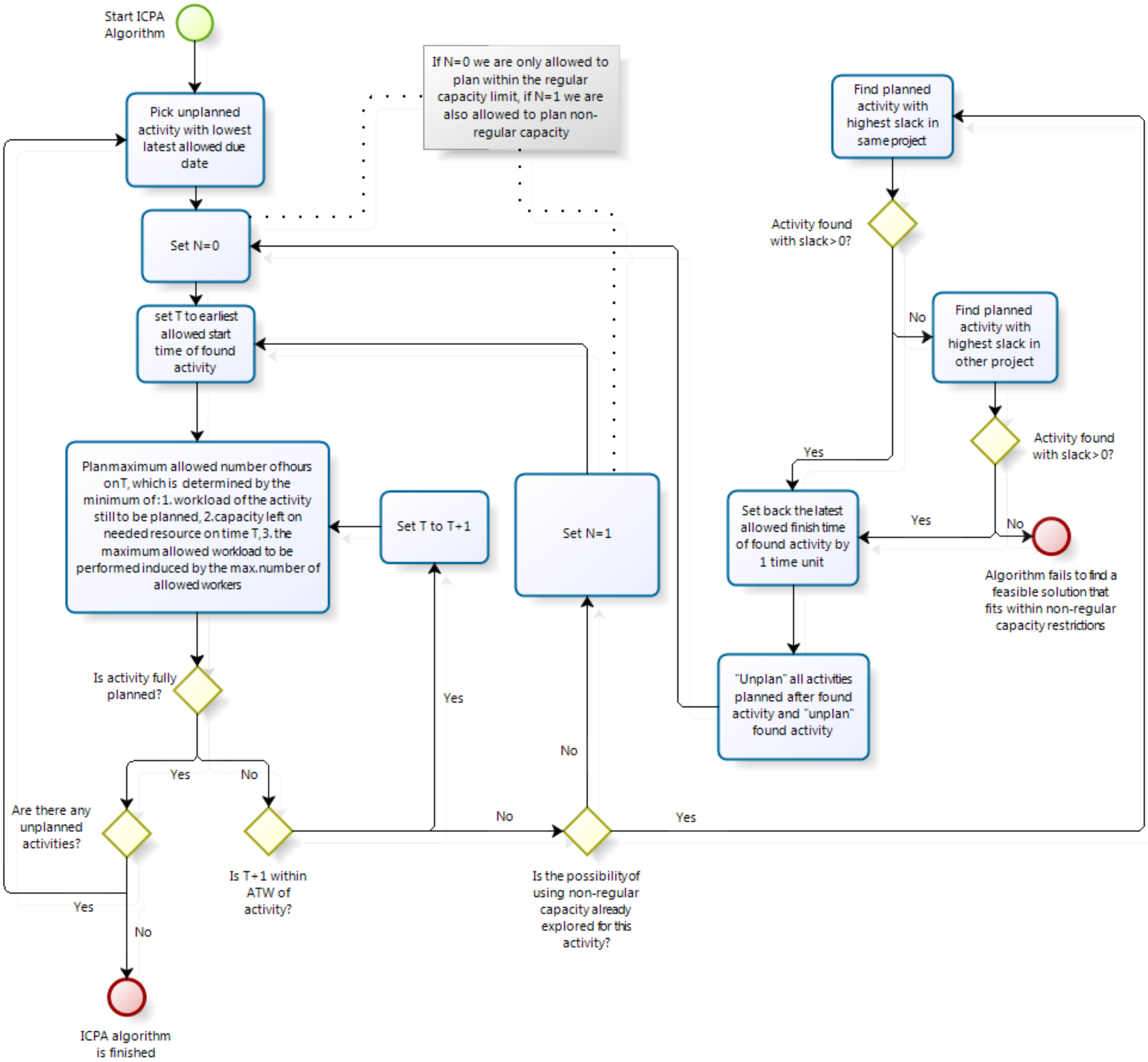

Figure 56: Augmented ICPA

Appendix VII: Augmented ICPA Example

This example explains how Augmented ICPA works by means of two examples. Recall that Augmented ICPA is an extension of the ICPA with a goal of staying within the limits of non-regular capacity.

The second example proves that Augmented ICPA does not always find a feasible tactical plan, even where a feasible solution to the planning problem exists.

Example 1:

Consider a project with three activities (a_1, a_2, a_3) that need processing on respectively the resources r_1, r_2, and r_3. The project should be finished at the start of week 11. *Table 15* displays the relevant activity data: minimum allowed duration and the number of FTEs needed of a resource to complete the activity.

Activities:	**Minimum Allowed Durations:**	**FTE needed for processing:**
a_1	3 weeks	3 FTE
a_2	2 weeks	2 FTE
a_3	3 weeks	3 FTE

Table 15: Activity data (Example 1)

Table 16 shows how much FTEs are left in each week for each resource. This number is the regular plus non-regular capacity that is left (before planning the considered project).

Resource:	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
r_1	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**
r_2	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**
r_3	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**1**

Table 16: Resource availability data (Example 1)

We employ Augmented ICPA algorithm to plan these three activities. Activities a_1 and a_2 are planned according to *Table 17*.

Activity:	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
a_1	**X**	**...**	**X**	**X**						
a_2					**X**	**...**	**X**			
a_3								**X**	X	X

Table 17: Project plan construction 1 (Example 1)

Since r_3 is unavailable at t=8, there is no more room to plan activity a_3. There are, however, slack activities in the project. Both a_1 and a_2 are slack activities with a slack of one week. Augmented ICPA algorithm proceeds by re-planning all activities that have been planned after (and including) the latest planned activity from the set {a_1, a_2}. In this case a_2 is re-planned and its latest allowed finish time is reduced by one. So the new ATW of a_2 is t=5 to t=6. From *Table 18* we can see, however, that we are not able to fully plan a_2 in its new ATW, because we would have to exceed the non-regular capacity restriction of resource r_2 on t=6.

Activity:	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
a_1	**X**	**...**	**X**	**X**						
a_2					X	**X**				
a_3										

Table 18: Project plan construction 2 (Example 1)

Luckily, there still is one slack activity in the project, which is a_1. Therefore, Augmented ICPA algorithm proceeds by reducing the latest allowed week in which processing is allowed for a_1

from t=5 to t=4 and by re-planning the activity. These actions result in a feasible tactical project plan (*Table 19*).

Activity:	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10
a_1	**X**	**X**	**X**							
a_2				**X**	**X**	**...**				
a_3							**X**	**...**	**X**	**X**

Table 19: Feasible project plan (Example 1)

The difference between ICPA and Augmented ICPA is that ICPA would have exceeded the non-regular capacity constraints, in the situation of *Table 17*, by partly planning a_3 on t=8. If non-regular capacity constraints were added to ICPA as a hard restriction, the ICPA algorithm would not be able to find a feasible tactical plan.

Example 2:
Consider two activities (a_1, a_2), both activities need processing on the same resource r_1. Activity a_1 should be finished at t=5 and activity a_2 should be finished at t=4. The release date of both activities is t=0. *Table 20* displays the relevant activity data: minimum allowed duration and the number of FTEs needed of a resource to complete the activity.

Activities:	Minimum Allowed Durations:	FTE needed for processing:
a_1	4 weeks	4 FTE
a_2	2 weeks	2 FTE

Table 20: Activity data (Example 2)

Table 21 shows how much FTEs are left in each week for each resource. This number is the regular plus non-regular capacity that is left (before planning the considered projects).

Resource:	t=1	t=2	t=3	t=4	t=5
r_1	**1**	**2**	**2**	**1**	**0**

Table 21: Resource availability data (Example 2)

We employ Augmented ICPA algorithm to plan these activities. Activity a_2 is already planned according to *Table 22*.

Activity:	t=1	t=2	t=3	t=4	t=5
a_1	**X**	**X**	**X**	X	X
a_2	**X**	**X**			

Table 22: Project plan construction 1 (Example 2)

We see in *Table 22* that activity a_1 does not fit, given the way activity a_2 is planned. We cannot plan a_1 on t=1, because there is no more capacity at resource r_1. We can also not plan a_1 on t=5, because that is after the activity due date. It is not possible to plan activity a_1. Since there is no slack in the system the algorithm stops here, without finding a feasible project plan.

Table 23, however, depicts a feasible solution for the problem instance. We can conclude that, even though a feasible solution to the planning problem exists, Augmented ICPA did not find a feasible tactical plan.

Activity:	t=1	t=2	t=3	t=4	t=5
$\boldsymbol{a_1}$	**X**	**X**	**X**	**X**	
$\boldsymbol{a_2}$		**X**	**X**		

Table 23: Feasible project plan (Example 2)

This example proves that Augmented ICPA does not always find a feasible tactical plan, even where a feasible solution to the planning problem exists.

Appendix VIII: Results Of Varying Workload

This appendix displays the full results of varying the workload in tabular form (*Table 24* to *Table 34*). We have varied "X" from .5 (halve workload) to 1.5 (50% extra workload compared to the base problem instance). We compare four solution approaches: ICPA, Augmented ICPA (which only finds solutions for X=.5 and X=.6), the LP-heuristic (H_{feas}) with an objective of minimising hours of non-regular time used, and the LP-heuristic with an objective of minimising the cost of non-regular hours used. The second columns of the tables show the time it takes the approaches to find a solution, the third column shows the number of non-regular hours needed for the plan, the fourth column shows the associated costs, and the last two columns show the two fluctuation measures described in Section 4.1.

For an interpretation of the results we refer to Section 4.5.1 in the main text.

X=.5	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	4.100	213.125	5.358	1.892
Aug. ICPA	<1	10.188	510.377	5.361	1.682
LP-Heuristic (obj.: min. hours)	50	3.112	159.846	3.255	2.285
LP-Heuristic (obj.: min. costs)	51	3.112	159.846	3.265	2.293

Table 24: Test results for X=.5

X=.6	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	5.851	302.843	5.857	2.038
Aug. ICPA	<1	12.447	620.482	5.835	1.803
LP-Heuristic (obj.: min. hours)	69	4.407	227.747	3.472	2.383
LP-Heuristic (obj.: min. costs)	95	4.563	235.106	3.446	2.384

Table 25: Test results for X=.6

X=.7	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	8.257	423.046	6.337	2.246
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min. hours)	59	6.180	313.413	3.651	2.452
LP-Heuristic (obj.: min. costs)	122	6.196	313.718	3.679	2.408

Table 26: Test results for X=.7

X=.8	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	10.925	556.274	6.717	2.296
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min.	70	8.504	431.907	3.821	2.476

hours)					
LP-Heuristic (obj.: min. costs)	122	8.761	439.563	3.812	2.493

Table 27: Test results for X=.8

X=.9	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	14.230	709.799	7.137	2.353
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min. hours)	79	11.043	553.642	4.113	2.678
LP-Heuristic (obj.: min. costs)	53	11.090	555.220	4.126	2.719

Table 28: Test results for X=.9

X=1	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
Current Plan	X	32.138	1.618.158	7.493	2.004
ICPA	<1	17.783	882.960	7.465	2.431
Aug. ICPA	<1	X	X	X	X
LP-Heuristic (obj.: min. hours)	108	17.143	847.195	4.552	3.070
LP-Heuristic (obj.: min. costs)	38	17.847	880.501	4.625	3.117

Table 29: Test results for X=1 (base problem instance)

X=1.1	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	21.833	1.082.976	7.785	2.564
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min. hours)	80	18.990	934.466	4.673	3.158
LP-Heuristic (obj.: min. costs)	52	18.993	932.621	4.622	3.177

Table 30: Test results for X=1.1

X=1.2	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	26.308	1.311.709	8.125	2.635
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min. hours)	25	26.172	1.289.483	5.026	3.230
LP-Heuristic (obj.: min. costs)	14	26.172	1.289.483	5.018	3.216

Table 31: Test results for X=1.2

X=1.3	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	30.596	1.534.779	8.422	2.700
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min. hours)	47	27.410	1.350.589	5.021	3.181
LP-Heuristic (obj.: min. costs)	58	27.454	1.349.042	4.975	3.295

Table 32: Test results for X=1.3

X=1.4	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	35.424	1.787.597	8.759	2.771
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min. hours)	60	32.702	1.607.528	5.202	3.430
LP-Heuristic (obj.: min. costs)	61	32.614	1.602.847	5.211	3.604

Table 33: Test results for X=1.4

X=1.5	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	40.064	2.021.888	8.982	2.820
Aug. ICPA	X	X	X	X	X
LP-Heuristic (obj.: min. hours)	60	37.258	1.841.757	5.539	3.700
LP-Heuristic (obj.: min. costs)	81	37.195	1.831.235	5.510	3.690

Table 34: Test results for X=1.5

Figure 57 to *Figure 60* depict the effects of varying workload on the four performance indicators considered.

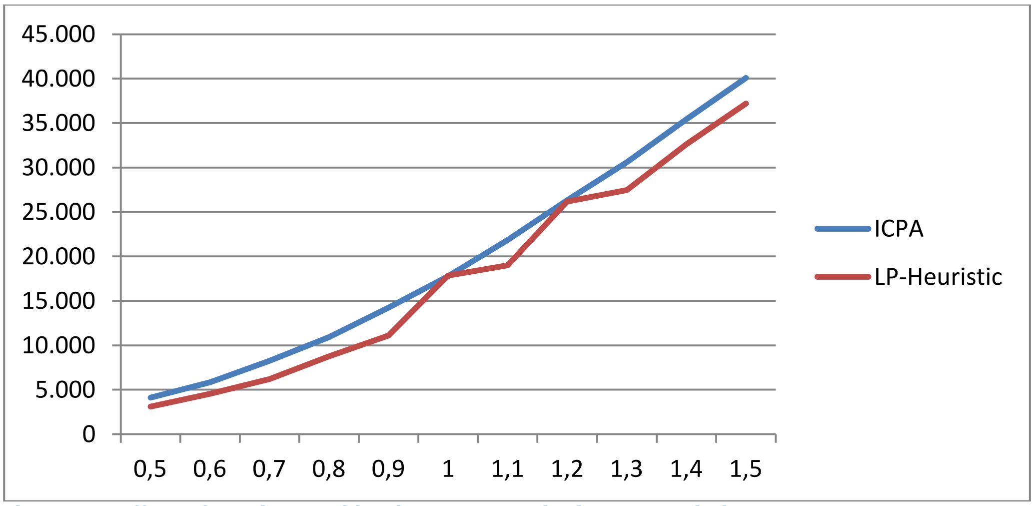

Figure 57: Effect of varying workload on non-regular hours needed

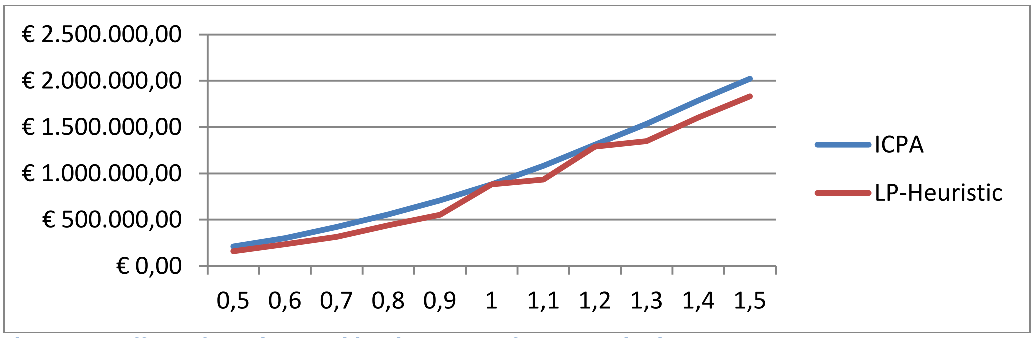

Figure 58: Effect of varying workload on cost of non-regular hours

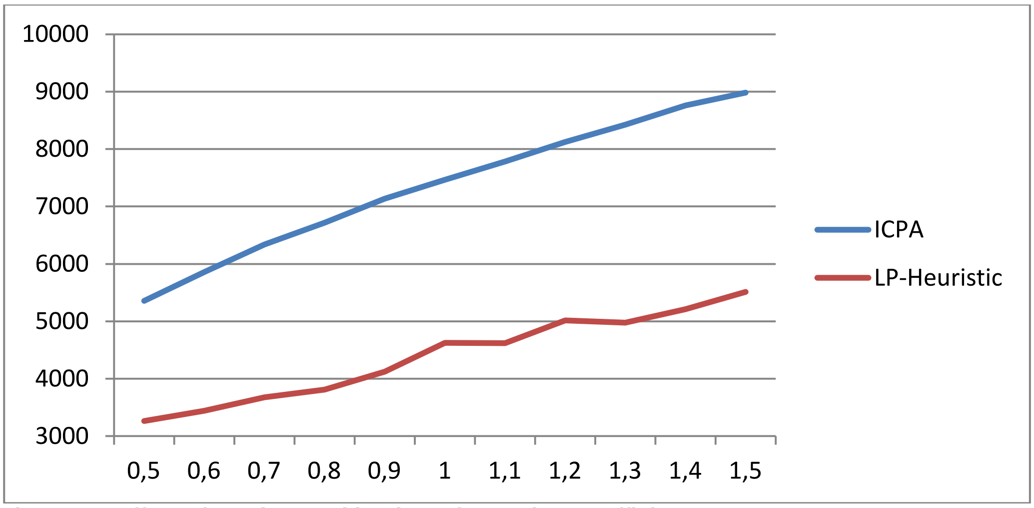

Figure 59: Effect of varying workload on Fluctuation Coefficient I

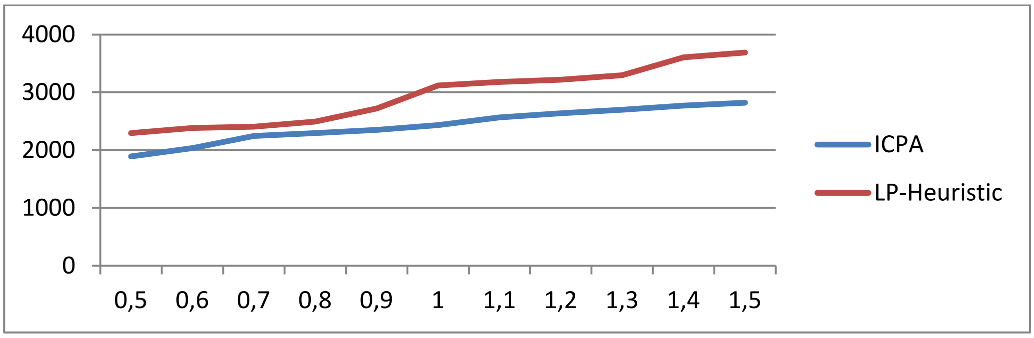

Figure 60: Effect of varying workload on Fluctuation Coefficient II

Appendix IX: Results Of Varying Due Dates

This appendix displays the full results of varying the due dates of projects in tabular form. For an interpretation of the results we refer to Section 4.5.2 in the main text.
Table 35 to *Table 40* show the results for varying the due date of project 3.

Due date p=3 t-3	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.940	891.714	7.468	2.406
LP-Heuristic (obj.: min. costs)	25	17.670	881.489	4.568	3.093

Table 35: Test results for: project 3, due date = 47

Due date p=3 t-2	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.868	886.935	7.476	2.409
LP-Heuristic (obj.: min. costs)	31	17.820	880.235	4.611	3.024

Table 36: Test results for: project 3, due date = 48

Due date p=3 t-1	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.826	885.112	7.466	2.423
LP-Heuristic (obj.: min. costs)	24	17.647	873.129	4.616	3.091

Table 37: Test results for: project 3, due date = 49

Due date p=3 t+1	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.731	880.438	7.685	2.416
LP-Heuristic (obj.: min. costs)	34	17.444	863.265	4.567	2.950

Table 38: Test results for: project 3, due date = 51

Due date p=3 t+2	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.670	877.164	7.470	2.425
LP-Heuristic (obj.: min. costs)	78	17.383	858.354	4.584	2.931

Table 39: Test results for: project 3, due date = 52

Due date p=3 t+3	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.777	882.409	7.694	2.410
LP-Heuristic (obj.: min. costs)	67	17.281	853.635	4.557	2.945

Table 40: Test results for: project 3, due date = 53

Figure 61 displays the effect of varying due date of project 3 on cost of non-regular hours.

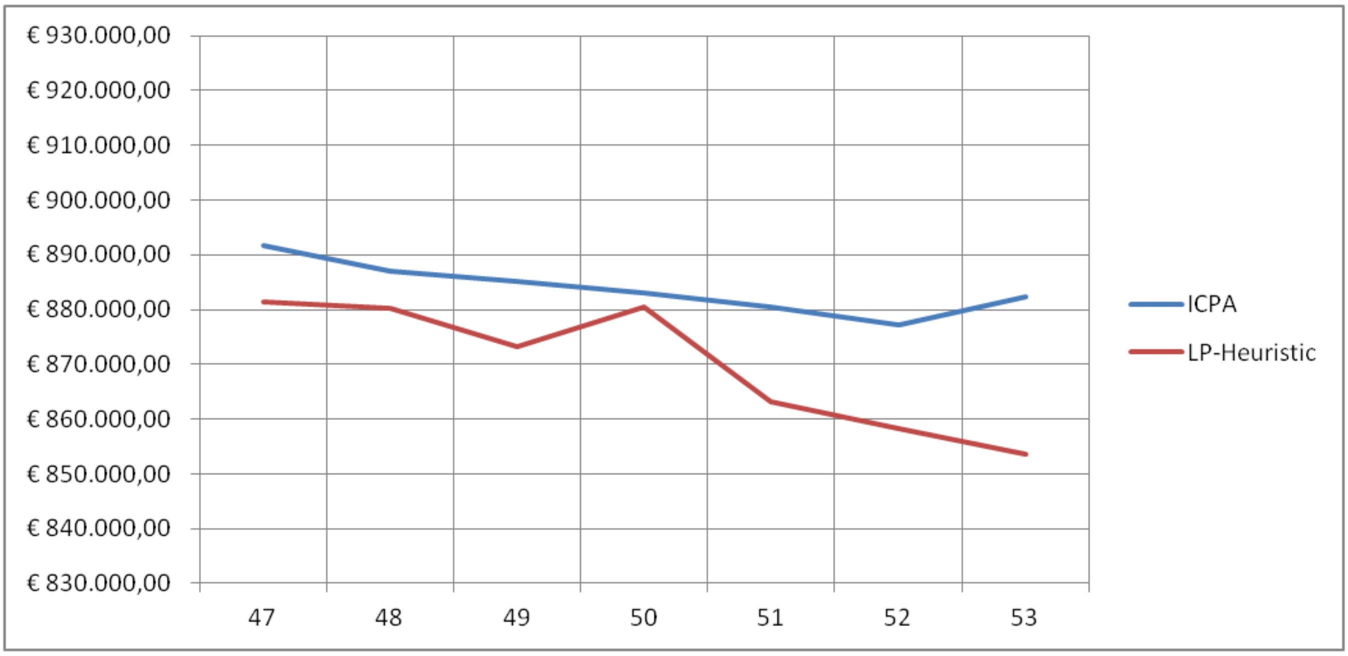

Figure 61: Effect of varying due date of project 3 on cost of non-regular hours

Table 41 to *Table 46* show the results for varying the due date of project 12.

Due date p=12 t-19	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	23.027	1.181.538	7.571	2.363
LP-Heuristic (obj.: min. costs)	96	22.859	1.172.192	5.051	2.986

Table 41: Test results for: project 12, due date = 52

Due date p=12 t-15	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	22.816	1.111.627	7.569	2.389
LP-Heuristic (obj.: min. costs)	166	22.555	1.106.258	5.038	2.971

Table 42: Test results for: project 12, due date = 56

Due date p=12 t-10	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	21.457	1.065.060	7.599	2.377
LP-Heuristic (obj.: min. costs)	53	20.493	1.013.367	4.890	2.849

Table 43: Test results for: project 12, due date = 61

Due date p=12 t-5	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	18.774	934.739	7.594	2.405
LP-Heuristic (obj.: min.	59	18.552	928.328	4.724	3.033

costs)					

Table 44: Test results for: project 12, due date = 66

Due date p=12 t-1	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.798	883.900	7.462	2.435
LP-Heuristic (obj.: min. costs)	37	17.913	883.382	4.494	3.083

Table 45: Test results for: project 12, due date = 70

Due date p=12 t+1	Time (sec.)	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II
ICPA	<1	17.783	882.960	7.465	2.431
LP-Heuristic (obj.: min. costs)	49	17.137	849.544	4.795	2.994

Table 46: Test results for: project 12, due date = 72

Figure 62 displays the effect of varying due date of project 12 on cost of non-regular hours.

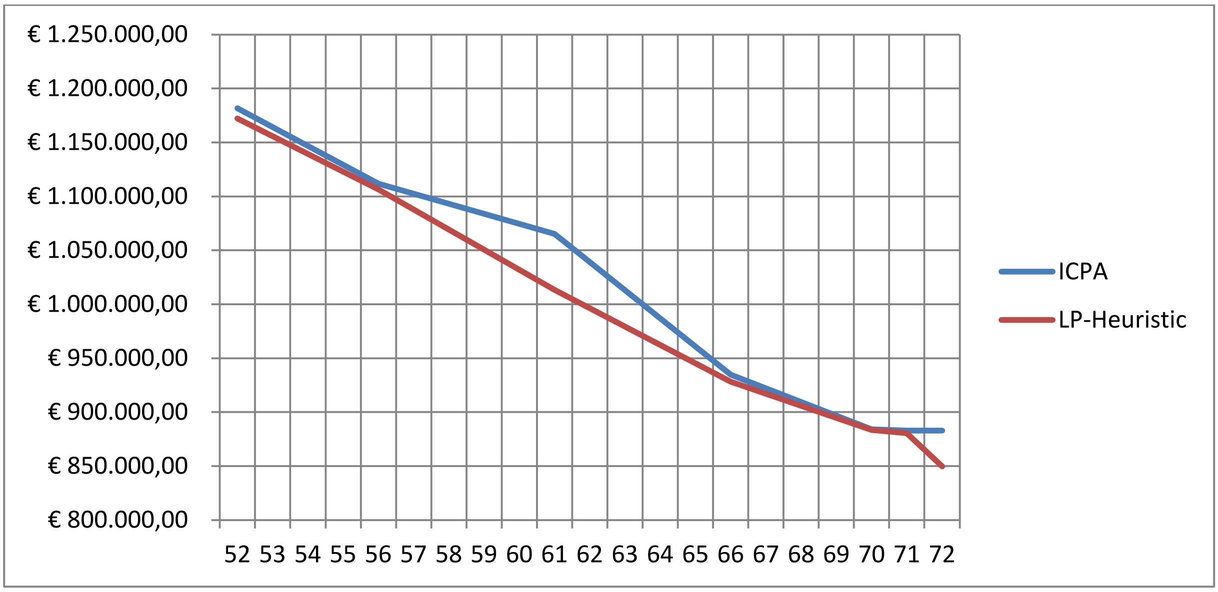

Figure 62: Effect of varying due date of project 12 on cost of non-regular hours

Appendix X: Results Of Varying Non-Regular Capacity Levels

This appendix displays the full results of varying the non-regular capacity levels of various resources in tabular form. The example exists of 6 projects, with each a maximum of 5 steps that need to be performed in serial. *Application I* is employed to perform the experiments (see *Appendix V* for the applications).

Figure 64 displays the relevant characteristics of the projects considered in this example. Per project the start and due dates are given, as well as their activities with their workload in units of 40 hours and the maximum number of workers that is allowed to work on an activity simultaneously. *Figure 63* displays the simple precedence relations of project activities. Each activity is performed by the capacity group with the corresponding name. At the bottom, *Figure 64* displays the regular capacity (in FTEs) and the cost of using one FTE of non-regular capacity.

Figure 63: Precedence relations of project activities

	Project 1: workload	max	Project 2: workload	max	Project 3: workload	max
Engineering	4	2	6	3	8	4
Work Preparation	2	2	2	2	4	2
Assembly	30	6	16	4	20	4
Programming	4	1	3	1	8	2
Testing	1	1	1	1	1	1
	start	due	start	due	start	due
Date	0	15	0	15	0	16

	Project 4: workload	max	Project 5: workload	max	Project 6: workload	max
Engineering	0	0	6	2	0	0
Work Preparation	4	2	2	2	2	2
Assembly	20	4	30	6	30	4
Programming	4	1	6	2	8	2
Testing	1	1	3	3	4	2
	start	due	start	due	start	due
Date	0	16	0	18	0	17

Weekly Capacity:	Engineering	Work Preparation	Assembly	Programming	Testing
Regular	2	4	10	3	2
Non-regular costs	60	50	40	70	70

Figure 64: Characteristics of example projects

Figure 65 displays the required capacity demand over time and per resource, for the example in *Figure 64*, constructed by ICPA, when there are no constraints to the maximum non-regular capacities.

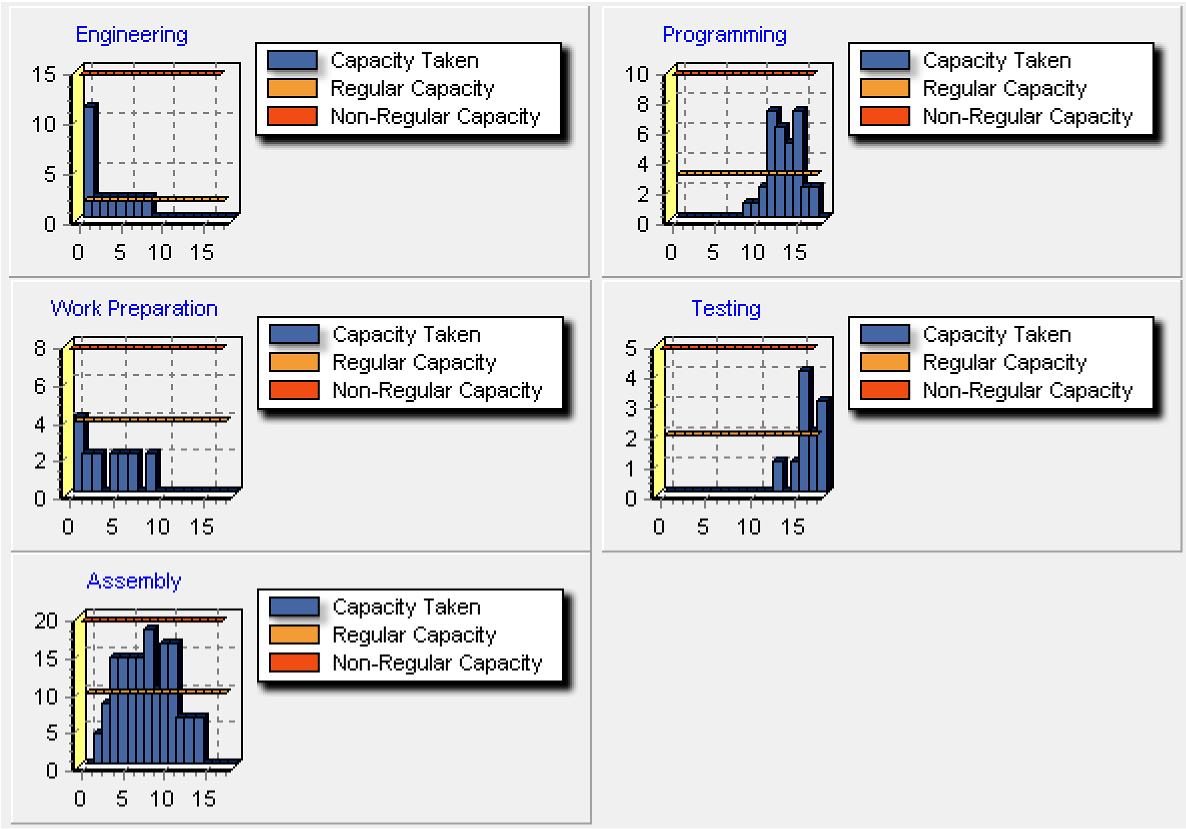

Figure 65: Capacity demand for several capacity groups, with no non-regular capacity restrictions

Table 47 displays in the first row the performance on the considered performance measures of the tactical plan resulting from standard ICPA, so with no restrictions to the allowed number of non-regular hours per capacity group. The remaining rows in *Table 47 give* the results of setting restrictions to the non-regular capacity requirements, where the leftmost cell in each row gives the restriction or restrictions that have been set to the maximum number of allowed non-regular hours for a certain capacity group.

Aug. ICPA	Non-regular hours	Non-regular cost (€)	Fluctuation Coefficient I	Fluctuation Coefficient II	Row Number
No restrictions	61	3.100	131,896	314,505	1
ENG max. 8	62	3.160	132,590	319,688	2
ENG max. 6	60	3.040	132,088	316,991	3
ENG max. 4	62	3.160	133,139	313,476	4
ENG max. 2	60	3.040	132,711	304,991	5
ASS max. 6	63	3.180	132,595	296,293	6
ENG max. 6; ASS max. 6	62	3.120	132,787	298,779	7
TES max. 1	58	2.830	132,510	300,242	8
TES max. 0	79	3.780	142,593	247,792	9
PRO max. 3	60	2.970	133,449	287,365	10
PRO max. 2	80	3.850	141,480	272,969	11
PRO max. 3; TES max. 1	60	2.970	133,449	287,365	12
ENG max. 6; TES max. 1	57	2.770	132,702	302,728	13
ENG max. 4; TES max. 1	59	2.890	133,753	299,212	14
ENG max. 2;	57	2.770	133,325	290,728	15

TES max. 1					
ENG max. 6; TES max. 0	78	3.720	143,209	285,765	16
ENG max. 4; TES max. 0	74	3.600	141,905	286,459	17
ENG max. 2; TES max. 0	72	3.480	141,547	252,586	18
ENG max. 6; PRO max. 2	79	3.790	142,364	286,065	19
ENG max. 4; PRO max. 3	61	3.030	134,692	286,335	20
ENG max. 6; PRO max. 3; TES max. 1	59	2.910	133,640	289,850	21

Table 47: Results of varying the non-regular capacity levels of several resources

The effects of varying the non-regular capacity levels of various resources in *Table 47* vary consideraly. For instance, varying the non-regular capacity limit of Engineering (row 2 to 5) has little effect on the objective values (even though the maximum capacity used in week does change). If we vary the non-regular capacity limits of Programming (row 11) or Testing (row 9), on the other hand, the hours needed and the costs increase, when the limit of where Augmented ICPA is able to find a feasible plan is reached. Also, when the non-regular capacity restrictions of various capacity groups are decreased simultaneously, the effect on the performance indicators is difficult to predict.

Appendix XI: Results Of Varying Regular Capacity Levels

This appendix displays the full results of varying the regular capacity levels of various resources in tabular form. For an interpretation of the results we refer to Section 4.5.3 in the main text. *Table 48* gives for four capacity groups the effects on non-regular hours and cost of non-regular hours, when a certain number of hours is added to the regular capacity of that capacity group. *Figure 66* depicts the effects of adding FTEs to various departments on cost in a graph.

Electric Wiring	Non-regular hours	Non-regular cost (€)	Jig Assembly	Non-regular hours	Non-regular cost (€)
+ 40 hours	17.172	854.973	+ 40 hours	16.943	843.459
+ 80 hours	16.651	832.592	+ 80 hours	16.103	805.659
+ 120 hours	16.256	815.581	+ 120 hours	15.263	767.859
+ 160 hours	16.100	808.877	+ 160 hours	14.423	730.059
+ 200 hours	15.918	801.079	+ 200 hours	13.583	692.259
+400 hours	15.841	797.755	+400 hours	11.170	583.674
Mechanical Assembly	**Non-regular hours**	**Non-regular cost (€)**	**PLC Assembly**	**Non-regular hours**	**Non-regular cost (€)**
+ 40 hours	17.239	857.878	+ 40 hours	16.923	828.820
+ 80 hours	16.625	831.451	+ 80 hours	16.131	780.482
+ 120 hours	16.072	807.692	+ 120 hours	15.395	735.610
+ 160 hours	15.705	791.906	+ 160 hours	14.734	695.255
+ 200 hours	15.428	780.016	+ 200 hours	14.215	663.637
+400 hours	14.777	752.015	+400 hours	14.013	651.310

Table 48: Effects of increasing regular capacity to various departments on cost

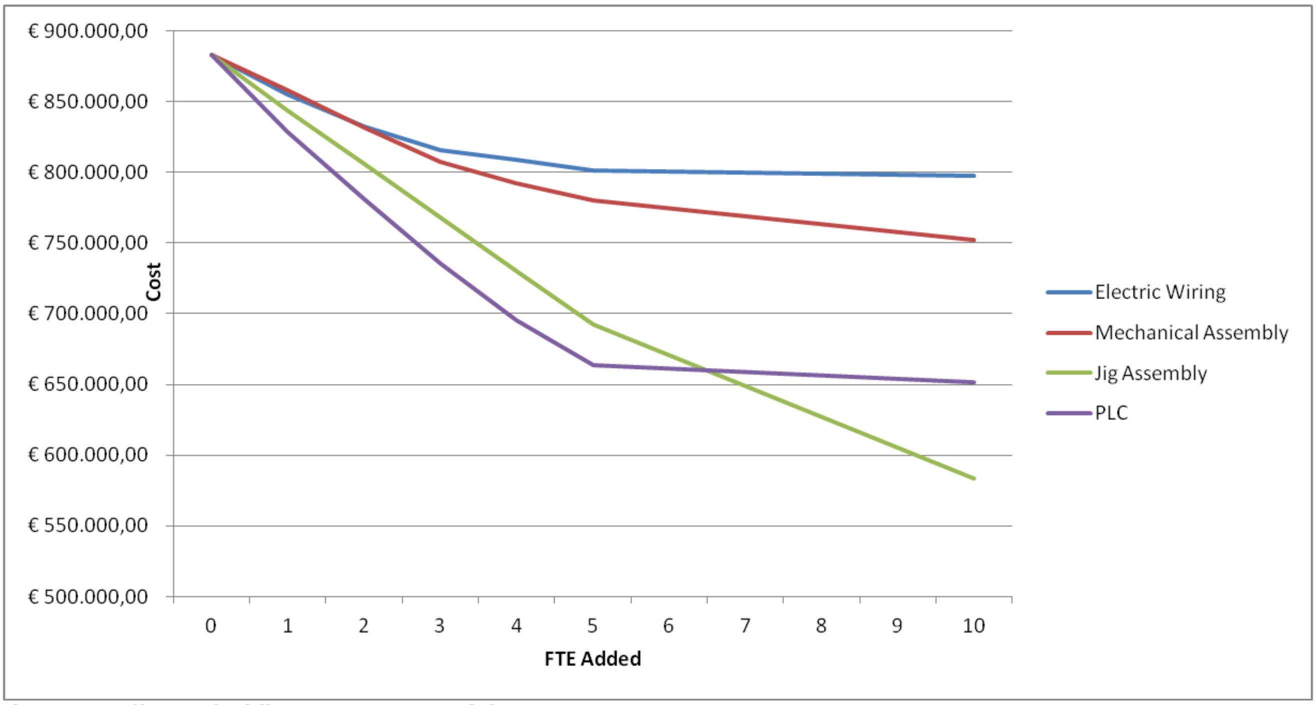

Figure 66: Effects of adding FTEs to several departments on cost