MASTER

Dynamic assignment and cross-training of workers at FEI Electron Optics

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Dynamic Assignment and Cross-Training of workers at FEI Electron Optics

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Abstract

The scope of this master thesis is the testing and final assembly of transmission electron microscopes (TEM) of FEI Company. FEI has experienced problems due to their lack of insight in their own capacity.
Using queuing theory and literature on hierarchical cross-training, suggestions were made for the total workforce and the training of engineers. Using dynamic assignment a schedule can be made to efficiently assign engineers to orders. This schedule will ensure that more orders are finished within the required quarter and reduce waiting times for FEI. Further more the schedule will give FEI a better insight into their capacity availability.

Management summary

Problem statement

FEI is the producer of electron microscopy systems for companies all over the world. The systems can be divided into transmission electron microscopes (TEM), scanning electron microscopes (SEM) and small dual beam systems (SDB). Customers may be found between universities and research centers, but also in industry. Besides the sales of these microscopes, FEI is involved with after sales activities, such as maintenance and repairs.
The production of these electron microscopes consists of the production of the base, including the column, followed by the testing of the column and the final assembly of the base with all desired accessories. The scope of this master thesis is the testing of the base and the final assembly of the TEM systems. These steps are performed by an engineer, preferably one engineer per system.

FEI has realised a problem has grown in the past years. Orders often exceed their deadline of the end of the quarter and the results for other orders are hard to determine, mostly because FEI has not the means of knowing what the capacity availability of the future will be. Therefore, the following problem statement has been formulated.

Initial problem statement

Currently, FEI does not have enough insight into the capacity availability. As a result work orders are delayed and deliveries no longer meet their deadlines. FEI would like to be better prepared and prevent these problems.

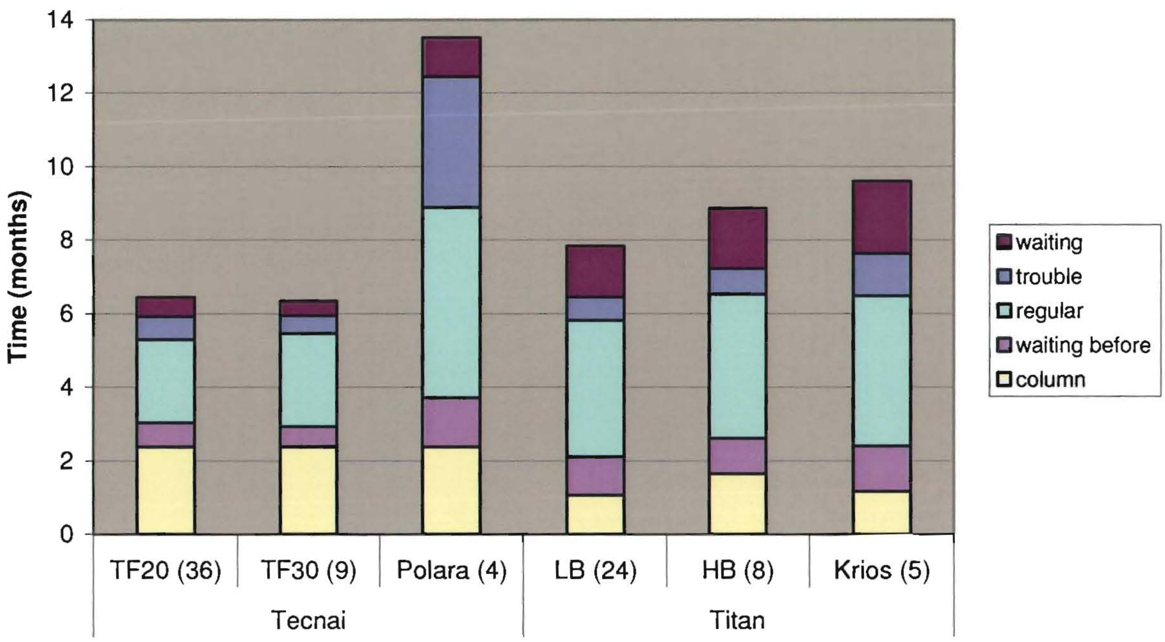
The problem involves engineers who have different, overlapping capabilities, thus we are dealing with flexible or cross-trained capacity; and the scheduling and training of engineers. In literature models can be found for the planning and scheduling of flexible and cross-trained capacity and the planning of training. However, there are no models that combine both aspects of this problem. Therefore, the following research question has been defined:

Research question

Analyze the production and planning at FEI and confront it with methods that can be found in literature. Design a model and a tool to give an overview of the availability of capacity and determine the time for training. Furthermore, design the tool as such, that it would give insight in the consequences of alterations to the current schedule on the timeliness of future orders.

Analysis

In order to assess the extend of the problem, the production times and the buildplan variations were analyzed. One of the causes of orders exceeding their deadlines is the cycle time of the microscopes. The cycle time of a microscope consists of the time to build a base, regular production time, trouble time and waiting times both before and during production. FEI pursues a delivery response time of 6 months for TF20 systems and TF30 systems, and of 9 months for other TEM systems. In order to meet this response time, the cycle time should be less than the delivery response time.



Average cycle times per system type

The figure above, shows that for four of the six systems even the average cycle time exceeds the response times. The waiting times of TF20 need to be decreased by 37% and for TF30 and Krios by 36% and 19% respectively in order to decrease the average cycle times within the response time. Unfortunately the variance of the cycle time war rather high, thus, even if the average cycle time will decrease till under the desired response time, many orders will still cross this limit.

The production of each microscope consists of several production steps. For each step, the average production time was determined. The ratio of the actual production times, regular and trouble, to the expected production times, based on the average times per step, is assumed to be normal distributed with mean 1,02 and standard deviation 0,22. This results in a coefficient of variance of 0,21. This distribution may be used to set a safety lead times for each order and to set the due date when an order arrives.

One of the results of the insufficient insight in capacity, are the variations in the buildplan. The buildplan is a plan of FEI what to produce each quarter. This plan is updated every month and every month the buildplan changes significantly. The buildplans of the first month of each quarter were compared. Due to insufficient capacity, the number of order in the buildplan of each system was decreased by 10 to 30% from the beginning of the quarter to the actual production. This is an average reduction of 2,2 systems every quarter. This indicates a capacity shortage. Buildplan should be made to better fit the available capacity.

Solutions

The solutions suggested in this master thesis are threefold. First of all queuing theory was used to determine the desired workforce. The buildplan can be translated into an expected workload. It is possible to hire the minimum amount of engineers, needed to carry this load, but due to the stochastic arrival and production times, this would result in long waiting times. In this report a trade-off is made between the costs of hiring an engineer, approximately

€50.000,-, and the average holding costs, approximately €75.000,- for every week of holding. Results showed that three additional engineers are required for both Tecnai and Titan

As stated earlier, the production at FEI is done by cross-trained engineers. There is a special kind of cross-training used at FEI, called hierarchical cross-training. This means that engineers first learn basic skills before learning additional skills. In literature little attention has been paid to this phenomenon. Therefore, a model was created to determine a minimum skill matrix. To fully fill the skill matrix would result in unnecessary investments for training, scarcely filling it will result in unwanted waiting times. Using the production schedule tool, the skill matrix is further filled in order to deal with the stochastic order configurations and find a balance between unnecessary investments and unwanted waiting times.

The main part of the solution is a tool for the scheduling of the engineers. Dynamic assignment is used to find an optimal schedule for the situation at FEI. The advantage of this model is that each possible assignment is assigned a contribution, which can be fully designed to the wishes of FEI. Dynamic assignment then maximizes the total contribution, resulting in an efficient schedule. This schedule can for instance include engineers and orders to wait for another order or engineer, even though an assignment is possible directly. However if a future assignment is more contributing, assignment is postponed.

The chosen dynamic assignment algorithm also allows for a schedule with a longer time horizon. This way, the resulting schedule can also be used to determine an expected due date for each order.

Results and conclusion

Current planning was compared to dynamic assignment, to see the improvements that may be gained by dynamic assignment. As a third scheduling method, the dynamic assignment tool was run without using future information.

For the 46 orders assigned in chapter 6, queuing theory suggested 17 engineers. The model of section 5.2.2 suggested a skill matrix, which was later updated using dynamic assignment. Results showed that the choice of skill matrix, strongly influences the efficiency of the schedules of all models. Current planning benefitted the least from the skill matrix, since the skills of an engineer do not affect the assignment decision. The dynamic assignment tool without future information (k=1) is basically an alteration to the current planning. Instead of letting the first available engineer start an order and if necessary letting a second engineer finish the order, performed considerably less than letting each engineer produce the entire order, especially when the skill matrix was better filled.
Dynamic assignment on the other hand performed even better than the assignment of one engineer to each order, but this difference slimmed when the skill matrix was better filled. The dynamic assignment tool performed better than the current planning for all skill matrices, but for a better filled skill matrix, the results did not differ much from the assignment of one engineer to each order .

Although queuing theory assumes that all engineers are capable of all orders, dynamic assignment agreed with the choice for this number of engineers. Even though, this evaluation was made using production times with less variance, the required workforce estimated by queuing theory was close to the number of engineers required by dynamic assignment. Only the height of the waiting times was strongly affected by the chosen skill matrix.

Stochastic production times strongly affected the dynamic assignment. The results were barely any better than the results for the current planning. If FEI could decrease the variance of the production times (already an objective of FEI), dynamic assignment would perform much better.

The training was well implemented into the dynamic assignment tool. The results show improvements of the number of order that were assigned, and thus started during the year in which the start was planned, the number of orders finishing within the planned quarter and average waiting times. The tool was able to decide on training and made assignment such that the engineers could improve their skills.

The model suggested in this master thesis should help FEI decide on the workforce size and training, both which trainings and when the trainings should take place. Furthermore, the tool should give FEI more insight into the availability of engineers and foresee problems that may occur, as late orders. Due to the variance in production times, the waiting times are decrease by only 10%. However when FEI is able to reduce this variance, benefits may be much higher.

Preface

In front of you lies the master thesis of Marieke de Heer, written as final project of Industrial Engineering & Management Science from the Eindhoven University of Technology. After four and a half years of preparation, each student should fulfil one last project.

I was fortunate enough to find a project at FEI Company, a manufacturer of electron microscopes. The project was challenging and interesting and the willingness of FEI to improve where possible, has made this project a most pleasant experience. In this project I investigated the current capacity for the production of transmitting electron microscopes (TEM). Using different models, I suggested a way on deciding the workforce size and training. Furthermore, I designed a tool, using dynamic assignment, which should help FEI Company schedule their engineers efficiently to their orders.

I could not have done this project without the help of some people, whom I would like to thank:

First of all I would like to thank Tarkan Tan, my primary supervisor at Eindhoven University of Technology. He helped me find my master this project and guided me through the project. His enthusiasm and guidance has helped me push my own limits and broadened my view on the subject. I would also like to thank my second supervisor, Rob Broekmeulen. He showed me a direction for my solution I had not thought to look. He helped me by making me consider different aspects of the solutions presented in this thesis.

From FEI, I would like to thank Loek Halmans, who found me this project. Unfortunately, he did not stay to see it finished. I would like to thank my supervisors at FEI: Marcel Sikkelerus, who helped me find answers to my questions, and Hans van Pelt who helped me find new questions to answer.

Finally, I would like to thank my family and friends for supporting me throughout my entire studies and the past few months for the completion of this project.

Marieke de Heer
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Part I Orientation

1. FEI Company

FEI is the producer of electron microscopy systems for companies all over the world. Customers may be found between universities and research centers, but also in industry. Besides the sales of these microscopes, FEI is involved with after sales activities, such as maintenance and repairs.
In 1949 Philips Electron Optics (PEO) was founded. It was one of the first companies to start production of large quantities of transmission electron microscopes. FEI was founded in 1971 in the US and aimed to provide high-purity, oriented single crystal materials for field emission research. Over the years FEI and PEO have developed many new techniques that could be incorporated in their products. In 1997 FEI and PEO merged into the current FEI Company, with the division FEI Electron Optics located in Eindhoven.

FEI has three sites, FEI Micro Electronics and FEI Beam Technology located in Hillsboro, Oregon, USA; FEI Electron Optics in Eindhoven, The Netherlands; and FEI Electron Optics in Brno, Check Republic. These sites are responsible for manufacturing and research & development. FEI provides sales and services in about 50 countries. In little over half of these countries FEI is actually present in the form of Sales and Service Departments (SSDs), in other countries the microscopes are sold through independent agents. These agents fall under the SSDs of FEI North America, FEI Asia Pacific Region, FEI Japan and FEI Europe.

The total net sales, gross profit, operating income and net income over the last nine years is shown in figure 1.

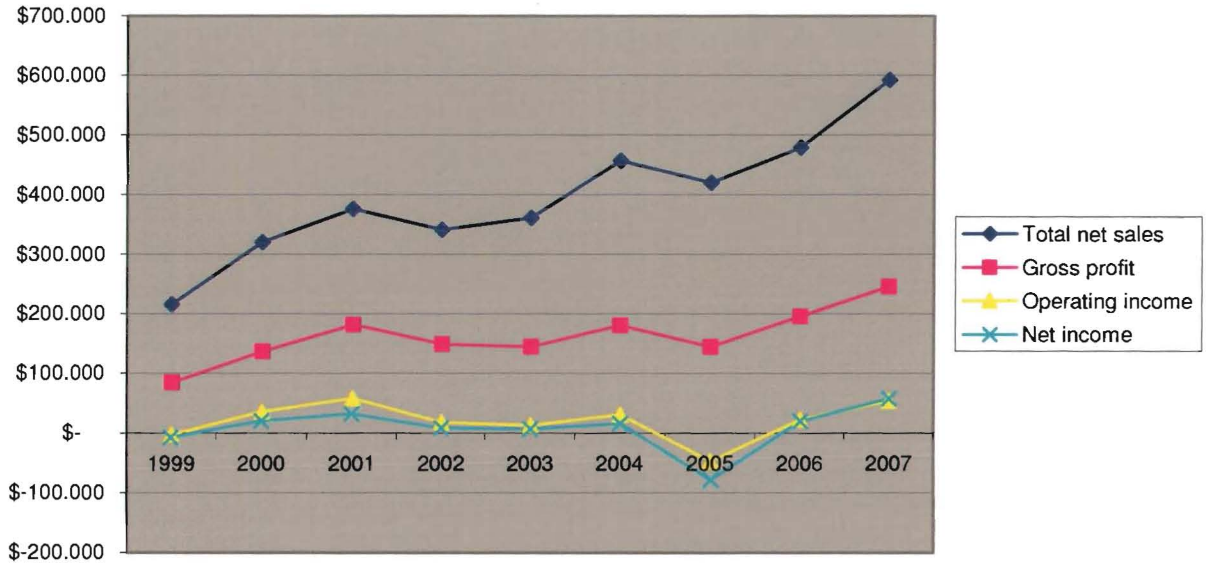


Figure 1: Financial results over the years (in thousands of dollars)

1.1 Core technologies and products

FEI focuses on four technologies for the products they produce:

- **focused ion beams** can be used to modify sub-micron surfaces;
- **focused electron beams** can be use to analyse, image and measure sub-micron surfaces;
- **beam gas chemistries** increases the effectiveness of the ion and electron beam and allows for etching and positioning of materials on sub-micron surfaces;
- **system automation and sample management tools** provide faster and easier access to the data from the systems.

The products that FEI produces using these technologies are:

- **scanning electronic microscopes** (SEM) produce an image of the surface of a sample by using a focussed electron beam;
- **transmission electronic microscopes** (TEM) create an image of a sample by sending a electron beam through the sample;
- **focussed ion beam systems** (FIB) are powerful tools for imaging, nano-manipulation and fabrication;
- **dualbeam systems**, a combination of FIB and SEM on one platform.

1.2 Market segments

FEI operates in three market segments, NanoElectronics; NanoResearch and Industry; and NanoBiology market. The NanoElectronics market consists of customers in the semiconductor, data storage and related industries such as printers and micro-electromachanical systems. The products are primarily used in laboratories to aid new product design, defect analysis, root cause failure analysis and circuit edit for modifying device structures.

The NanoResearch and Industry market includes universities, public and private research laboratories and industrial customers, such as automobiles, aeroplanes, metals, mining and petrochemicals. The products are used for development, analysis, production, root cause failure analysis and quality control applications.

The customers in the NanoBiology market may be found among universities and research institutes engaged in biotech and life science applications, and among pharmaceutical, medical device and hospital companies. The products help cell biologists and drug researchers to create detailed 3D reconstructions of complex biological structures, enabling them to map proteins within cells.

In 2007 FEI realized revenue of $ 592.5 million. FEI reports their revenue based on these market segments. A last segment is service and components, delivered to all previously mentioned segments. The revenue is divided over the segments as shown in figure 2.

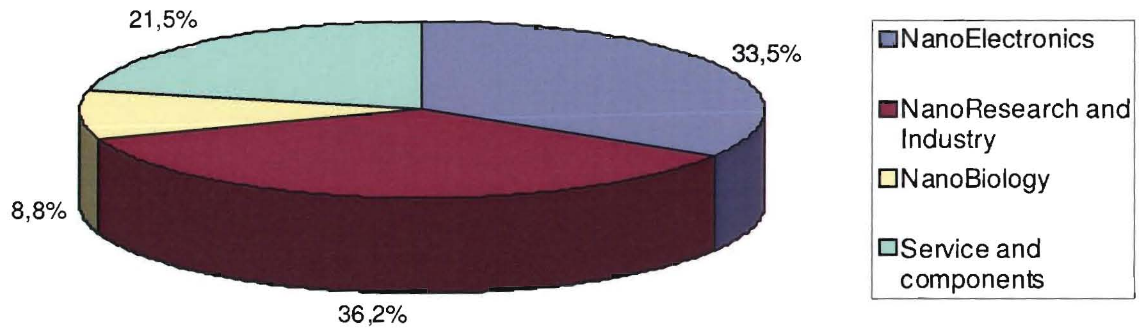


Figure 2: Net sales by segment

The markets are located world wide. The revenue geographically distributed is shown in figure 3.

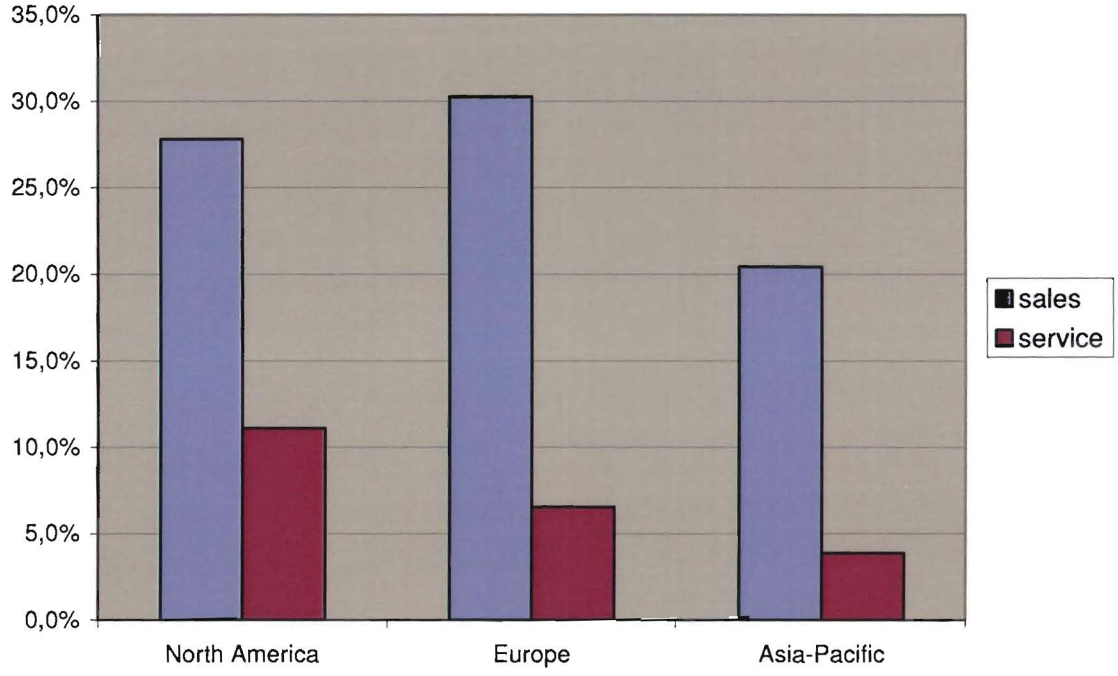


Figure 3: Net sales by geographic region

1.3 Employees

At the end of 2007 FEI had 1,820 full-time employees and 46 temporary employees worldwide. From these 1,866 employees, 345 work in Research & Development and 358 in Sales & Marketing. Other employees work in Manufacturing and General & Administration.

2. Problem definition and research assignment

FEI Company is a leading supplier of advanced Tools for Nanotech (microscopes) to a broad range of markets. Nanotechnology is the science of characterizing, analyzing and fabricating objects smaller than 100 nm ($=100*10^{-9}$ m). FEI develops and produces the microscopes and is involved in after sales service.
The aim of this master thesis will be the production department of FEI Electron Optics. This department produces scanning and transition electronic microscopes and small dualbeam systems (SEM, TEM and SDB). This master thesis will be aimed mostly at the TEM production, as it is more complex and it is expected that the results can easily be adapted for SEM/SDB.

The production process is build up of the production of the base, the tests of the base and the adding of options. Some of the bases are ordered from Brno, Czech Republic; others are produced in Eindhoven in a separate department. The microscopes are tested and assembled by engineers by hand. Each engineer is able to perform the necessary tests on the microscope and a skill matrix is available to show the different additional skills of each engineer needed for the adding of the options.
Planning is done in the logistics department and the production department together. First, logistics creates a schedule, based purely on forecast for a horizon of one year. When an order arrives, the forecasted order best fitting the new order is replaced. Once it is time to start production, logistics maps out the order and production is responsible for finding an engineer to produce the order. Every week the progress of the orders is discussed.

2.1 Problem definition

Currently, there is little insight in the availability of engineers. When capacity is insufficient, scheduled work orders might fall behind. This causes more work in process, higher inventories and late deliveries. FEI would like to gain more insight in the capacity availability so that they may find a solution before it becomes a problem.

There is a small tool to consider if the planned production can be produced by the engineers. However, this tool does not take into account the specific skills of the engineers. If there is enough overall capacity to satisfy demand, but not enough capacity with a required skill, this tool shows that there is enough capacity.

This thesis should lead to a tool that takes the skill matrix of the engineers into account and that should help decide if a new engineer should be trained or an existing engineer should be trained further.

Initial problem statement

Currently, FEI does not have enough insight into the capacity availability. As a result work orders are delayed and deliveries no longer meet their deadlines. FEI would like to be better prepared and prevent these problems.

2.2 Research assignment

The problem involves engineers who have different, overlapping capabilities, thus we are dealing with flexible or cross-trained capacity; and the scheduling and training of engineers.

In literature models can be found for the planning and scheduling of flexible and cross-trained capacity and the planning of training. However, there are no models that combine both aspects of this problem. Therefore, the following research question has been defined.

Research question

Analyze the production and planning at FEI and confront it with methods that can be found in literature. Design a model and a tool to give an overview of the availability of capacity and determine the time for training. Furthermore, design the tool as such, that it would give insight in the consequences of alterations to the current schedule on the timeliness of future orders.

2.3 Deliverables and boundaries

The research question should be solved by creating a tool. The in- and outputs of the capacity decision process of FEI can be modelled using a multi-factor model for capacity expansion by Julka et al. (2007):

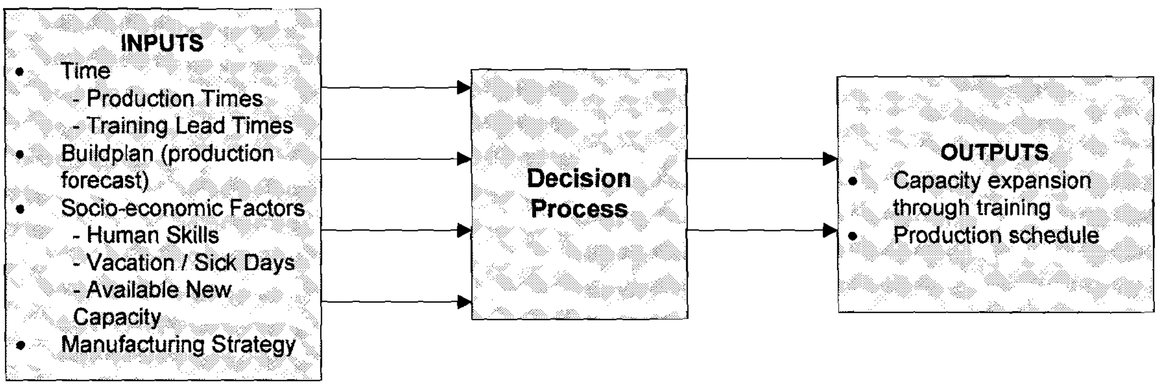


Figure 4: Inputs and outputs for the multi-factor model for capacity expansion at FEI

The objective of the decision process will be to minimize backlogs or tardiness and costs for holding inventory and giving training. By using weights or penalty costs a balance may be found between the two objectives. The model should decide the necessary trainings and show the production schedule, as suggested by figure 4. Most inputs speak for themselves. Manufacturing strategy involves aspects such as the sequence in which FEI produces incoming orders and the desire to produce with a parallel structure, and should give insight into what weights best fit the strategy of FEI.

The total capacity of the TEM production team will de decided on using information on expected orders, expected production time and expected waiting times. If necessary, new engineers will be trained to join the workforce. The objective is to create a more fluent production environment without increasing the workforce unnecessarily.

The tool should:

- determine what training is needed (train new engineers or train current engineers further) and determine if and when training is possible;
- distinguish between engineers with different skills;
- reckon with free time (e.g. holidays and national days off)
- be written in MS Excel (at the request of FEI), so that FEI can easily change the tool if the situation changes.

Boundaries of the tool are:

- the tool will be based on the scheduled production as known at that moment and will not take fluctuation of demand into account;
- the production of the microscopes is done by one engineer as much as possible.

2.4 Methodology

The methodology of this research is described using the research model of Aken et al. (2001), which is set up especially for Industrial Engineering and Management Science projects. According to Aken et al. (2001), research can be divided in a diagnostic phase (figure 5) and a design phase (figure 6). On the right side of figure 5 the result of the diagnosis phase can be seen. This phase should lead to better insight into the problem and to a possible solution. This is achieved by comparing an evaluation tool to the current practice at FEI (center column). The evaluation tool is created by reviewing literature on capacity planning and talking to managers and logistics at FEI and the input of the supervisors at the TU/e.

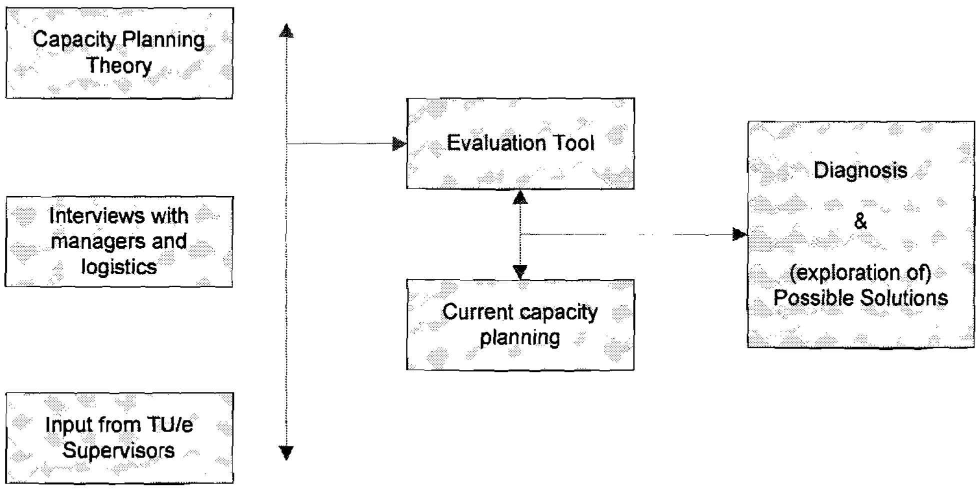


Figure 5: Research model for the diagnostic phase

The layout of the research model for the design phase (figure 6) is similar to that of the diagnostic phase. This phase should lead to the design and implementation of a tool that can be used to solve the problem of insufficient insight in the capacity availability. Information and theories form literature and talking to managers, logistics and TU/e supervisors can be used as guidelines for the design of the tool for capacity planning.

From the diagnosis phase it became clear the problem might be solved by dynamic assignment for the scheduling work and training for engineers; cross-training could be used to determine the required skills of engineers; and queuing theory could help determine the total number of engineers required.

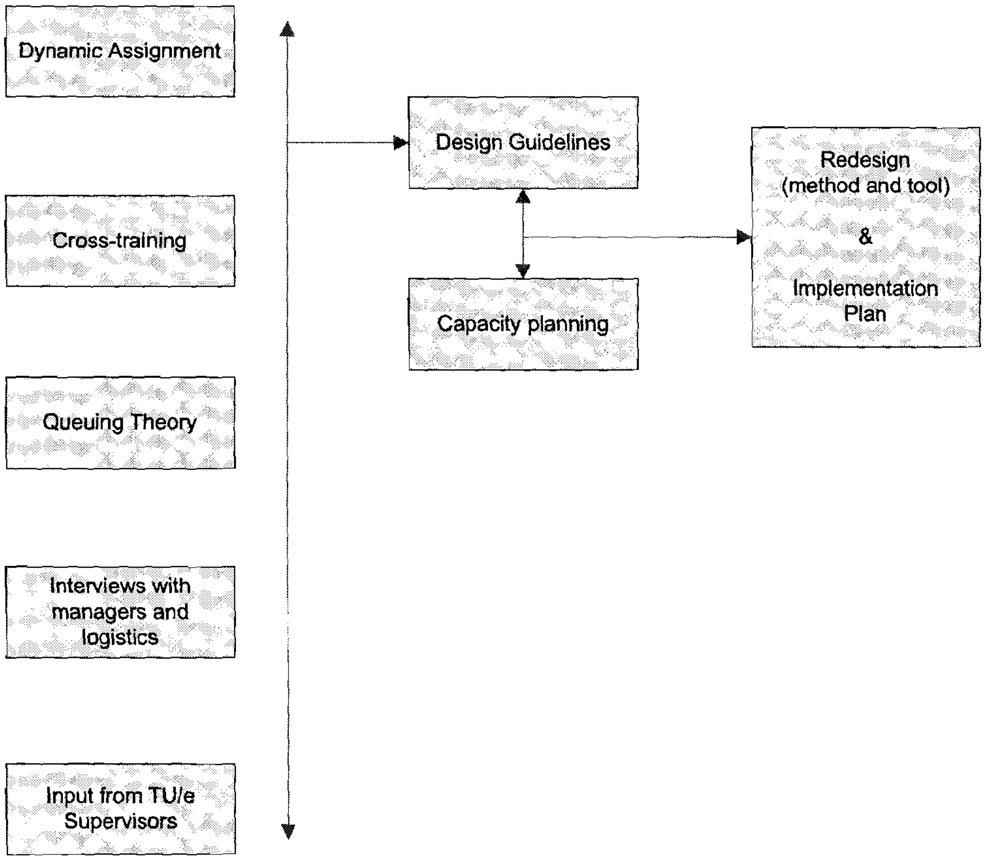


Figure 6: Research model for the design phase

2.5 Report layout

This report consists of three parts. This chapter is part of Part I, in which a general orientation towards FEI Company is given, the problem at hand has been discussed and in the next chapter the current situation is outlined, describing the layout of the departments in the scope of this master thesis; the current order flow; and the communication between departments.

The second part is the core of this report. First data on waiting times, production times and production plans are assessed in order to prepare data for the three main solutions, which are also shown in figure 6. For each of these solutions a short theoretical introduction will be given and alterations will be suggested for the implementation at FEI.

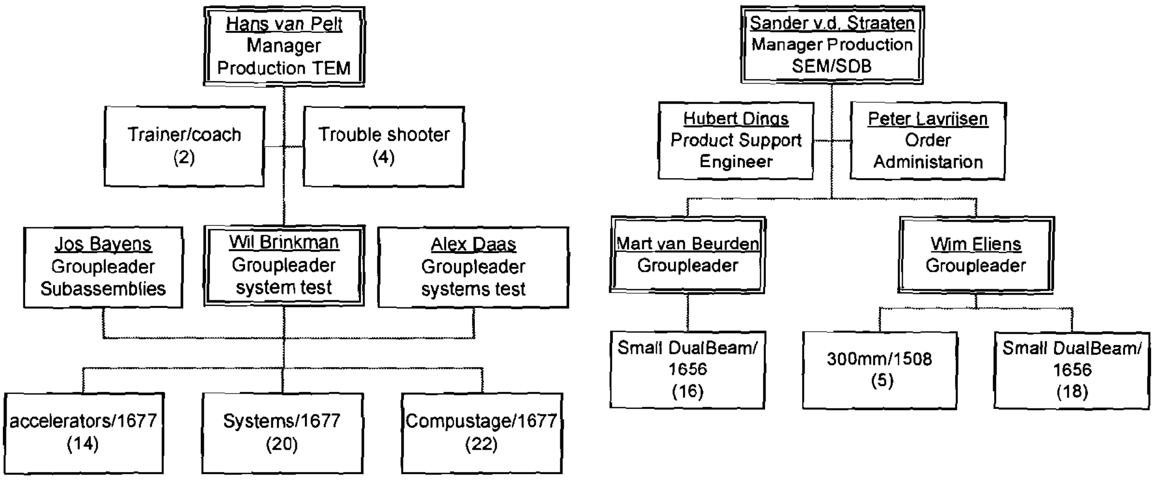
The last part will show the results that can be achieved through theses three solutions, discussing how the results will affect the planning at waiting times at FEI. An implementation plan will be shortly discussed and part III will be rounded up with a conclusion and some recommendations.

3. Current situation

The planning is currently done by the production department of TEM and SEM/SDB and the logistic department together. These three departments report to the operations department of Acht, Eindhoven. The position of the operations department within FEI Company is shown in Appendix A.

3.1 Production

The production at the site in Eindhoven is divided into two departments, TEM and SEM/SDB. Each department is responsible for the production of different product types. The transmission electron microscopes (TEM) are the Titan and Tecnai systems, the scanning electron microscopes and small dualbeam systems (SEM/SDB) are the Nova, Strata, Helios, V600 and Expida systems. These systems can be further specified in product types. The production departments are structured as follows as shown in figure 7.



a) TEM department **b) SEM/SDB department**

Figure 7: Structure of the production departments

A microscope consists of a base with a column in which the electron beam will run through the lenses and diaphragms, an accelerator on top of the column emits the electron beam, and several options can be built in or onto the microscope at the request of the customer. The options are for instance a camera, an image corrector, or a probe corrector.

The production of microscopes is usually done in three major steps. First a base, including a column, is build and the accelerator is installed. Second, the system is tested, an optics test should tune the beam produced by the accelerator, and a specifications test should confirm the specifications of the microscope. The last step of the process is adding the accessories or options.

3.1.1 Production TEM

The columns of the TEM systems are not similar for each product type nor for each customer. Customers may choose specifications for the column, such as the lenses used, the poles in the column, and if the column should be able to open or not. The bases for the Tecnai are produced at another site, at Brno. The bases of the Titan systems are produced at the site in Eindhoven.

3.1.2 Production SEM/SDB

The columns of SEM/SDB are equal for each system type. Again some columns are built in Brno and some are built in Eindhoven. The production time of SEM/SDBs is considerably shorter than the production time of TEMs.

3.1.3 Skill matrix

All engineers can perform the second step of production, the optics and specification tests. The accessories require specific skills and different accessories can be added by different engineers. FEI uses a skill matrix to note which engineer has what skills. FEI distinguishes between trainees, engineers who need support, engineers who do not need support, and experienced engineers. There are also trouble shooters, who can help the engineers if a problem occurs.

3.2 Logistics

The logistic department is responsible for the planning of the production, shipment and the purchasing of the components. The structure of the department is shown in figure 8.

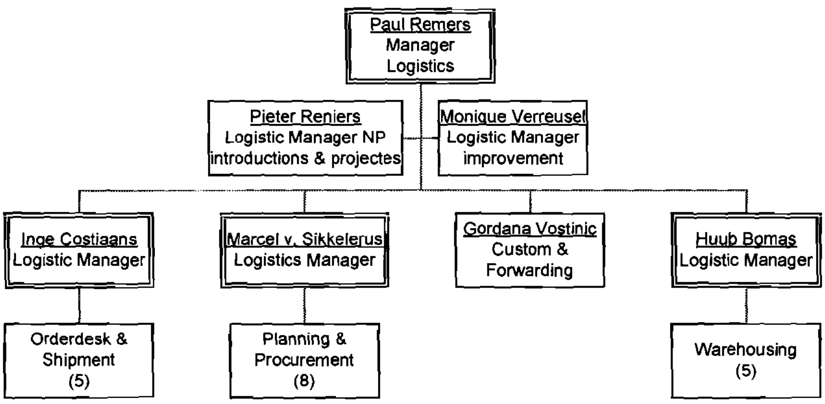


Figure 8: Structure of the logistics department

3.2.1 Order process

The process from order until delivery is depicted in Appendix B. The logistics department is not responsible for the contacts with the customers. Many countries have their own representative, called an account manager. They contact potential customers and if the customer is interested in buying a product, the account manager and the customer agree on a quote, which describes what the customer wants and when it should be delivered. The customer can place an order or make a reservation. A reservation is sometimes made if the customer is not sure if he can raise the money to take all the options he wants. The account manager estimates the probability the customer will go through with the order. In case a reservation is made, the product can still be produced, but upper management needs approve the start of production. In practice, all reservations are approved if the probability is high enough. If the probability is low, the account manager will know not to submit the quote.

The account manager enters the quote into the CRM database, the sales database for all orders and order leads. The SSD Backoffice, to which the account manager reports, checks the quote for legal implications. If the quote does not follow the law or company regulations, the account manager and the customer need to adjust the quote. If the SSD is satisfied, order acceptance is given. Then the quote comes in the scope of the logistics department.

The order desk retrieves the information from CRM and checks if the configuration of the quote is possible to produce. For instance, it sometimes occurs that a camera of a SEM system is added to the configuration of a TEM system. Some problems are created by SSD, others by the account manager. SSD checks the quote and determines who ought to correct the problem. When the quote is changed and the order acceptance is given again, the order desk gives the factory acceptance. An order is created in the database MFGpro.

Next planning and production determine the ship date of the product. Planning looks in MFGpro at the availability of the accessories and at the planning and commits to a certain ship date. Then production checks the availability of the engineers and commits on a ship date based on the availability of accessories and engineers. When both have submitted their commitments to the order desk, the order desk commits to the ship date and enters it into CRM. Planning creates a work order according to this ship date and production will start the production of the microscope. Progress is followed in weekly meetings and the order desk updates the data in CRM, if the ship date changes.

When the production is finished, planning closes the work order in MFGpro and shipping arranges the shipment. It is important that the product arrives at an agreed upon time, because the customer has to be present at the site for installation.

Procurement is charged with the purchasing of the components and accessories. MFGpro translates the order requirements based on the planning and bill of materials into components requirements. Based on the current stock level, MFGpro determines if an order is necessary. Each week, procurement prints out a list with the components that need to be ordered and orders those components.

3.2.2 Planning

The initial planning for production is completely based on the buildplan, a forecast of what will be produced and sold each quarter. Based on this buildplan a number of slots is created for each product type. The number of slots is equal to the expected production of a certain type that quarter. These slots are planned an entered in MFGpro. The situation for SEM/SDB is somewhat different than for TEM.

For the SEM/SDB systems the column is the same for each product type. When scheduling a microscope in MFGpro, planning creates two parts of an order. The column is the first part and the options are the second part. The planning of both parts depends on the forecast, but not in the same way. If 4 columns of a specific type are forecasted, 4 columns are planned. For each column an option list is created, which contains the probabilities that a specific option is ordered on the microscope. Thus, the second part of the order is a list of 0,45 camera, 0,1 image corrector, and so on. A product thus consists of a column and an option list.

The systems of TEM are a little more complex. The column is not the same for each product type. So first of all, the column is planned according to the buildplan, but the options within the column are estimated according to the forecast. The "external" options are not planned in an option list, but separately. If a certain camera is on 1 of the 10 systems and 8 systems are planned, 1 camera is planned in stead of 8 times 0.1 cameras. As a result a product consists of a column and several options.

When an order arrives, planning takes a look at the planning and selects the slot that best suits the order. In the case of SEM/SDB the column and an option list are selected and the probabilities are replaced by amounts. For TEM the column and the options are selected. When the order is ready for production, a work order is created, consisting of a 0-order and a 1-order. The 0-order is the production of the column; the 1-order is the final assembly of the column and all options. If there is a reservation instead of an order, the 0-order is started, but the 1-order starts only after an order is placed.

3.3 Meetings

Since production and logistics are both responsible for the timeliness of production, meetings are held to ensure the production can follow the schedule. Two meetings are held, for both meetings the tool designed in this master thesis should be applicable.

3.3.1 Monthly buildplan meeting

In this monthly meeting the number of slots for each product type is determined. Each slot represents an expected order. This decision is based on several variables:

- A forecast of incoming orders.
- Current orders in hand.
- The desired orders in hand or the desired response time.

Missing from the buildplan decision is a capacity constraint. The production managers are present, but there is no tool which easily translates the buildplan to a capacity requirement.

3.3.2 Weekly progress meeting

Every week the progress of each order is discussed. If an order runs late, productions and logistics try and find a solution. Sometimes this solution is to delay the order, sometimes the solution is sought in reallocating capacity. In the latter case the timeliness of one system is sacrificed for another. It is not possible to see the consequences for other systems due to the chosen solution. Minor fluctuations in production times can be taken care of by engineers working overtime.

Part II Research & Design

4. Analysis

In order to make the capacity availability more visible, it is important to have more insight of the production times and the buildplan. In the first section of this chapter the production times will be dissected and analyzed. Afterwards, the buildplan will be assessed in terms of variations and workload. For capacity availability it is not enough to determine the number of engineers. The engineers have different skills and different orders can therefore be produced by different engineers. Therefore, in the last section the current skill matrix will be analyzed.

4.1 Production and arrival times

The engineers record the time they spend on each step of the production and the time the machine lays still. The total cycle time consists of the time to build the column, regular and troubled production days and waiting time. To gain a better view of the production times, these aspects are assessed separately. First, the total cycle time will be analyzed to understand how it is build up. Afterwards the waiting times and production times are analyzed in the following two sections. Finally, some attention is paid to the interarrival times needed for the queuing theory.

The data of the production times consists of historical data of 49 Tecnai systems and 37 Titan systems. It was found in the progress files, which engineers fill in while working on an order. The data include information on time spend on each production step, on additional time spend on each step due to trouble, and on waiting times, including the causes of the waiting times.

4.1.1 Cycle time

The cycle time is the time from starting to produce the column till the final dismantlement before shipping. For Tecnai the column is built in Brno, the Titan column is built at the site in Eindhoven, but by a separate team. After the column is finished and available at the site in Eindhoven, an engineer can turn the column into a microscope. However, the orders do not arrive linear and neither do the engineers produce linear. This causes waiting times, when the columns are finished, but no engineers are available yet. Even when the production has started, waiting times still occur. Another cause of delay is technical trouble in the production. All these aspects of the total cycle time were assessed separately and rendered the results shown in figure 9. The numbers after the system types indicate the number of systems of that type included in the analysis.

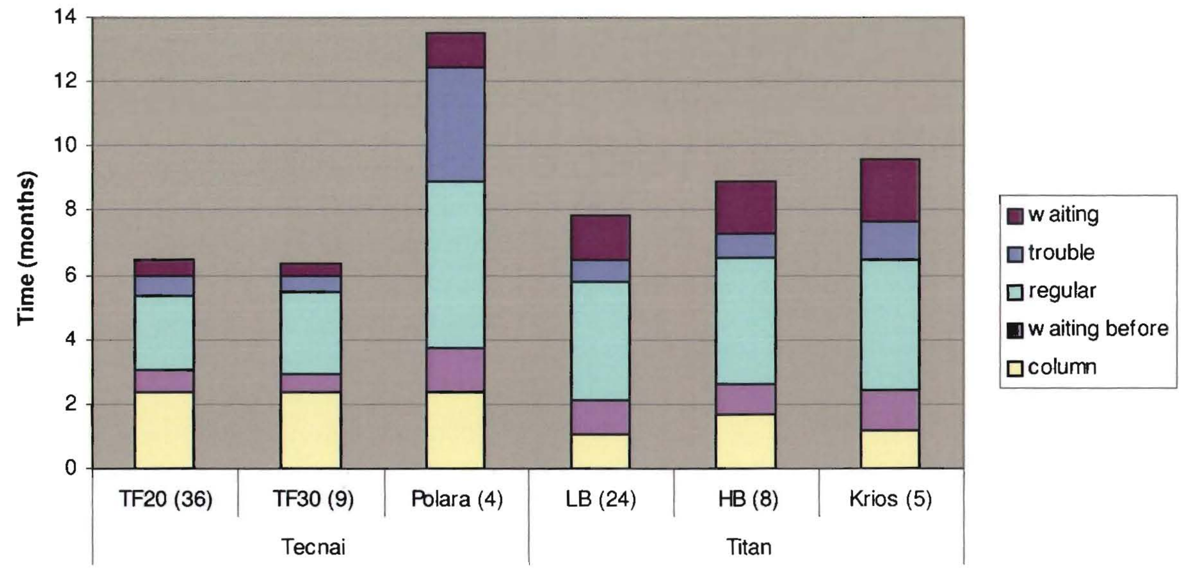


Figure 9: Average cycle times per system type

Figure 9 shows the total cycle time for each system type. It also shows on how many system's data the results were based. Especially for Polara and Krios there was little data available. Since these systems, especially Polara, show longer cycle times than the other systems, the results were discussed with experts at FEI. However, the experts at FEI did not find the longer production times for Polara striking, therefore, these data will be used for the rest of this analysis.

For the TF20 and TF30 a delivery response time of at most 6 months is desired, for the other systems 9 months is allowed. Figure 9 shows that four of the six system types meet this delivery response time on average. Polara exceeds this delivery response time extremely. For all systems decreasing the waiting times would be meaningful for the cycle time. The percentage of waiting during production is significantly different for Tecnai and Titan (two-sided t-test, P=0,010). Waiting before production does not show significant differences (two-sided t-test, P=0,224). There are no significant differences between the types of Tecnai or between the types of Titan. The waiting times before production accounts for 13% of the total cycle time. The waiting times during production for Tecnai is 12% and for Titan is 18%. The total waiting times (two-sided t-test, P=0,012) account for 23% of the Tecnai cycle time and for 36% of the Titan cycle time.
In order to bring the average cycle times of TF20, TF30 and Krios systems within the desired response time, a reduction of 37%, 36% and 19%, respectively, is needed. However, given the standard deviations in table 1, the cycle times of many orders will still exceed the response time.

	TF20	TF30	Polara	LB	HB	Krios
Mean	6,4	6,3	13,5	7,8	8,9	9,6
St. deviation	1,3	1,5	4,8	2,5	2,7	3,0
Coefficient of variance	0,21	0,23	0,35	0,32	0,31	0,31

Table 1: Cycle times per system type (in months)

To be able to decrease waiting times, the waiting times will first be further investigated in the next section.

4.1.2 Waiting time

For Tecnai systems the material costs are approximately €900.000,-. If this investment is not made, 10% profit may be reached (this percentage is used by FEI), thus the holding cost are 10% of the average inventory per year. If an order experiences waiting times, investments are made too early. This means that every week that an order is late, FEI will miss out on 10% of €900.000,-, thus €1.700,- is lost for every week of delay and every order. In the past year 43 Tecnai systems were sold. This means that the average waiting time of 1 week for Tecnai will be approximately €75.000,-. For Titan these costs are even higher.

The waiting times have already been divided into waiting time before and during the production. The waiting time during production can be further divided in waiting time caused by lack of capacity, engineers' days off or sick days, logistic problems or unknown problems. The proportion of each of these causes is shown in figure 10.

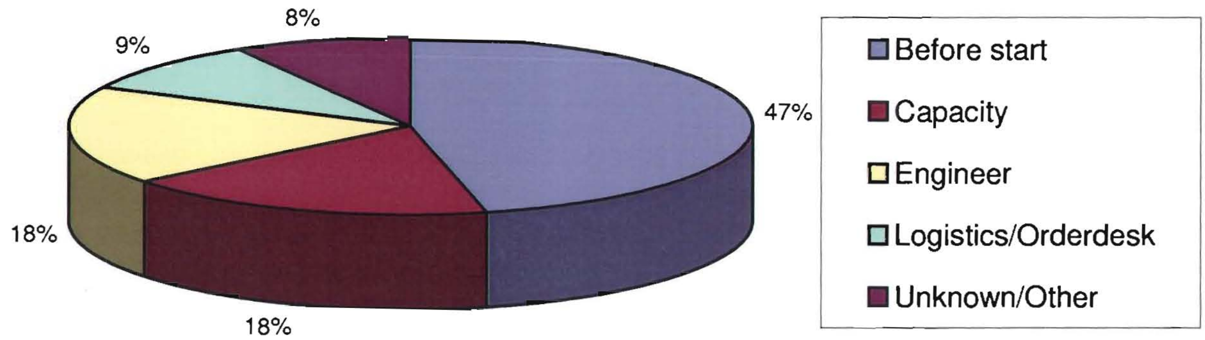


Figure 10: Causes of waiting for all systems

The lack of capacity was caused by the fact that a microscope did not have its own engineer, the engineer temporarily had to work on another microscope or because a trouble shooter or support was unavailable. Most of these causes could be eliminated by a good production scheduling and a proper workforce. The waiting times before the start are queues caused by lack of capacity. In section 5.1 the waiting times will be predicted using queuing theory. Using queuing theory, the size of the workforce can be determined by making a trade-off between expansion and waiting times.

The engineer's days off and sick days will always exist, however, they will be integrated into the capacity availability. Logistic or order desk problems are the lack of an order or order configuration (the system was started as a reservation, but can not continue without an order or configuration) and materials arriving too late. Neither of these problems are within the scope of this assignment, however, the timeliness of material will benefit from a good planning system, as the arrival of the materials can be timed based on this schedule.

4.1.3 Production time

For the queuing theory it is important to know what the production times are and what the coefficient of variation is. The production time will be defined as the time for regular and troubled production. Waiting times and the time required for the build of the column will not be included, because the engineer assigned to the order is not occupied with this order at that time.
The data per system type can attribute the variance partly to the stochastic production time and partly to the variation in configuration. Since the configurations are not included in the

queuing theory, this variation in configuration will be included in the variance on the production times. The results are shown in table 2.

	TF20	TF30	Polara	LB	HB	Krios
Mean	63,2	66,3	189,8	95,6	103,6	115,3
St. deviation	22,1	26,4	88,4	37,3	48,1	40,6
Coefficient of variance	0,35	0,40	0,47	0,39	0,46	0,35

Table 2: Production times per system type

The scheduling model uses deterministic information on production time and updates the planning as new information on production times becomes available. It is important for the planning to use the expected production time based on the configuration, as soon as it is known. The production times per production step are included in Appendix C.

For the determination of a safety lead time or safety capacity, deterministic production times will not suffice. There is insufficient data to determine the stochastic distribution of production times per configuration. Therefore, the ratio between production time, thus the cycle time excluding waiting times, and expected production time is determined and a distribution fitted. ANOVA showed no significant differences between the distributions of the six system types (Lavene's test P=0,618; ANOVA P=0,686).

Since the production consists of several sequential steps, it can be assumed that the production time per configuration and thus the ratio will follow a normal distribution. This hypothesis could not be rejected (P=0,554). Therefore, it will be assumed that the ratio follows the normal distribution with mean 1,02 and standard deviation 0,22. This results in a coefficient of variance of 0,21. This distribution may be used to set a safety lead times for each order and to set the due date when an order arrives.

The coefficient of variance of the ratio is considerably lower than the coefficients of the production times, since the variations of the configuration are no longer part of this variance.

4.1.4 Arrival times

For queuing theory, the inter-arrival times are also important. All arrival data of Tecnai was combined for the interarrival times for Tecnai and the same was done for Titan. The production is planned with an equal distribution of Tecnai and Titan systems over time and the type of systems are spread equally within distribution of arrivals. Therefore, the arrivals can be combined in to arrivals per system instead of per system type. The results are shown in table 3.

	Tecnai	Titan
Mean (in days)	6,34	9,12
Standard deviation	5,58	6,94
Coefficient of variance	0,88	0,76

Table 3: Coefficient of variance for the inter-arrival times

4.2 Buildplan

The buildplan is the master planning of the production at FEI. In the buildplan the expected number of systems that will be produced each quarter (the number of slots) is recorded. The production planning is based on this buildplan, until actual orders fill the slots. A production schedule, thus, depends strongly on the accuracy of buildplan.

The buildplan is not a forecast of sales or incoming orders, but it is still a forecast. It predicts the number of orders that will be produced each quarter. In order to evaluate the buildplan variations, it is possible to use common forecast error measures. These forecast error measures, which can be divided into standard and relative error measures, can be used to make a statement about the differences between forecasted and actual data. The standard measures are reported in the same units as the data that is evaluated, whereas, the relative measures are presented as an error percentage of the actual data. (Sanders, 1997)

The mean error (ME) and mean absolute deviation (MAD) are both standard measures, given by:

$$ME = \frac{1}{n}\sum_{t=1}^{n} e_t$$

$$MAD = \frac{1}{n}\sum_{t=1}^{n} |e_t|$$

Where n is the number of observations and $e_t = X_t - F_t$ is the error of the forecast (F_t) compared to the actual production (X_t). The mean percentage error (MPE) and the mean absolute percentage error (MAPE) are both relative error measures. These measures show the ratio between the error and the actual production.

$$MPE = \frac{1}{n}\sum_{t=1}^{n} PE_t$$

$$MAPE = \frac{1}{n}\sum_{t=1}^{n} |PE_t|$$

Where

$$PE_t = \frac{X_t - F_t}{X_t} \cdot 100\%$$

Sanders (1997) supposes an alteration for the case where $X_t = 0$ to avoid dividing by 0:

$$PE_t = \begin{cases} \dfrac{X_t - F_t}{X_t} \cdot 100\% & \text{for } X_t > 0 \\ \dfrac{F_t - X_t}{F_t} \cdot 100\% = 100\% & \text{for } X_t = 0 \end{cases}$$

However if the forecast is not 0 and the actual value is 0, the error should be negative, not positive as suggested above. In the analysis a negative error was used for those cases. If both forecast and actual data are 0, the error will be set to 0.

4.2.1 Variations due to capacity

During the buildplan meeting changes in the buildplan of coming two quarters are mostly caused by capacity shortages. If the buildplan one quarter in advance and the buildplan of the beginning of the quarter are considered as forecasts for the buildplan at the beginning of the quarter and the actual builds respectively, the results follow from the forecast measures are shown in table 4.

	One quarter in advance				Beginning of the quarter			
	ME	MAD	MPE	MAPE	ME	MAD	MPE	MAPE
TF20	0,2	0,6	0,018	0,072	-0,7	0,7	-0,105	0,105
TF30	0,0	0,4	0,083	0,217	0,2	0,4	0,133	0,233
Polara	0,1	0,3	0,000	0,200	-0,4	0,4	-0,300	0,300
Titan	0,1	0,7	-0,007	0,098	-1,3	1,5	-0,249	0,283
Total	0,4	1,2	0,013	0,064	-2,2	2,2	-0,131	0,131

Table 4: Buildplan variations due to capacity shortage

One quarter in advance all system types show that about deviations are of the same magnitude in both directions $(ME \approx 0)$. The positive changes are mostly caused by postponed orders from the current quarter; negative changes are mostly due to expected lack of capacity. At the beginning of the quarter, changes are more often negative and for TF20 and Polara completely negative $(ME \neq -MAD)$. Again positive changes do occur, but not as much and are caused because an order may, unexpectedly, be finished at the end of this quarter in stead of the beginning of next quarter.
TF30 is an exception, because the market is increasing slightly and more orders arrive than planned. This causes that TF20 or Polara may sometimes have to make way for an extra TF30.

The variations of the buildplan close to the production quarter could be prevented by implementing the capacity availability in the buildplan meeting. The production times can be used to determine the maximum systems to produce or the minimum number of engineers required to produce the buildplan. Using queuing theory, the expected waiting times can be used to see if the waiting times do not create a long cycle time.

4.2.2 Variations due to sales forecast

Variations in the buildplan more than one quarter in advance are mostly caused by changing forecasts. Again the changes per quarter are evaluated and the changes compared to the actual production are shown in table 5.

	Two and three quarters in advance				Three quarter in advance to actual			
	ME	ME	MAD	MPE	MAPE	MAD	MPE	MAPE
TF20	-0,15	1,05	-0,038	0,157	-0,8	1,4	-0,132	0,217
TF30	-0,35	0,45	-0,167	0,200	-0,5	0,5	-0,283	0,283
Polara	-0,1	0,3	-0,125	0,275	-0,5	0,9	-0,450	0,750
Titan	-0,5	1,1	-0,074	0,138	-2,2	2,4	-0,420	0,445
Total	-1,1	2,1	-0,065	0,115	-4	4,6	-0,245	0,281

Table 5: Buildplan variations due to forecast changes

The changes two and three quarters in advance are approximately half of the changes from three quarters in advance to actual production. A better forecast method may lead to a more constant buildplan and, thus, better planning.

4.3 Skills of the engineers

Currently the skill matrix is very little filled. It is not necessary to completely fill the skill matrix, because not all orders require a highly skilled engineer. How the skill matrix should be filled will be discussed in section 5.2. In order to determine the desired skill matrix, it is important to know the order configurations.

Graphic representations of the order configuration and skill matrices are shown in Appendix D.

4.3.1 Current skill matrix Tecnai

As can be seen in Appendix D, the engineers seem to have a hierarchical skill matrix, meaning that the skills is either a subset or a super set of the skills of another engineer. This is not a training necessity. The basic steps (ma, fc, of, hf and ad) need to be mastered by an engineer before he might start an additional training. If an engineer has not mastered the basic skills, he will not appear in the skill matrix, so those engineers can be overlooked. The sequence of the additional skills is not fixed.

A complete hierarchical skill matrix is not even desirable, because Appendix D also shows that the order configurations are not hierarchical. What skill matrices are desirable will be addressed in the next chapter.

Currently there is an undercapacity at Tecnai. Therefore, the capacity per skill will also experience an undercapacity. In order to assess the current skill matrix somewhat, the percentage of time engineers spend on an order that has a certain skill requirement in its configuration is compared to the number of engineers possessing that skill. Table 6 shows that the basic skills are not mastered by all engineers. These engineers need to complete the basic training before learning any additional skills. Furthermore, it is clear a camera is added to most of the machines. For cameras and gif there is not enough capacity even if there was enough overall capacity.

	ma	fc	of	hf	ca	gi	ed	st	ad
Engineers	100%	100%	100%	100%	80%	7%	67%	73%	100%
Orders	100%	100%	100%	100%	86%	32%	60%	65%	100%

Table 6: Engineers possessing a skill required by part of the orders for Tecnai

The order configurations in Appendix D shows that the options stem and edax only occur in combination with either a camera, gif or both. Furthermore, gif and a camera can be combined, but the combination only occurred without stem and edax or with both stem and edax.

4.3.2 Current skill matrix Titan

The skills matrix of Titan is not as hierarchical as for Tecnai. Like Tecnai, the basic skills need to bee mastered before starting a new training. Table 7 shows the percentage of working time is spend on an order with a specific skill and the percentage of engineers possessing a skill, but for Titan. The additional skills are camera, gif, edax, stam, image corrector, probe corrector, monochromator.

	kt	to	th	ca	gi	ed	st	ic	pc	mo
Engineers	100%	100%	100%	100%	33%	80%	80%	47%	27%	53%
Orders	100%	100%	100%	80%	80%	63%	80%	47%	43%	31%

Table 7: Engineers possessing a skill required by part of the orders for Titan

Again, even if overall capacity would be sufficient, there is a large undercapacity for engineers with the gif-skill and another undercapacity can be seen for engineers being able to add a probe-corrector. Again in the next chapter, improvements for the skill matrix will be discussed.

The order configurations show that only 5 systems do not require either stem or a camera, 3 of which are only basic systems without any options. Gif and cameras are more likely to be combined than for Tecnai.

5. Development of solutions

As could be seen in the analysis, the problem is threefold. First the capacity and buildplan are out of sink. This causes long waiting times before the orders are started up. The second and third part of the problem is waiting times during the production. This is caused mainly by shifts in order assignments, i.e. orders are started up by one engineer, but the engineer does not perform all tasks within that order, because the engineer does not possess the necessary skills to fulfil the order. By improving the scheduling method and the current skill matrix, the waiting times during production can be minimized.

Since the problem can be divided into three problems, the solution will also be threefold. Section 5.1 covers the tactical solution that deals with the lack of capacity and the waiting time before the orders are started up. It is undesirable for FEI to fully fill their skill matrix, because the training costs would become to high. Therefore, using the results of section 5.1 and literature, some suggestions are made for the filling-in of the skill matrix in section 5.2. Section 5.3 focuses on an operational solution, introducing a scheduling method based on dynamic assignment.

5.1 Total capacity

Variability in the arrival times and production times and high utilization cause waiting times. Queuing theory can be used to find the number of engineers required to produce the orders without too much waiting times. The following notations will be used:

$A \mid B \mid m \mid b$	*Kendall's notation* of a queuing model with four parameters
A	the distribution of interarrival times
B	the distribution of production times
m	the number of engineers in the system
b	the maximum number of jobs in the system (infinite in this case)
A and B can have the following values:	
D	constant (deterministic) distribution
M	exponential (Markovian) distribution
G	completely general distribution
WT	waiting time
c_a and c_e	coefficient of variance for the interarrival and production times
t_e	average production time
ρ	utilization of the engineers

5.1.1 General model description

The situation at FEI requires a $G \mid G \mid m$ model, since neither the inter-arrival times nor the production times follow a Poisson distribution. The $M \mid M \mid 1$ model is the easiest of the models. Hopp & Spearman (2000) formulated the expected waiting time is given by the following formula:

$$E\left[WT_{M|M|1}\right]=\left(\frac{\rho}{1-\rho}\right)\cdot t_e$$

A higher utilization will lead to longer waiting times. When there are more than one engineer, engineers will come available more often if the same utilization is met and waiting time will decrease:

$$E\left[WT_{M|M|m}\right]=\left(\frac{\rho^{\sqrt{2(m+1)}-1}}{m\cdot(1-\rho)}\right)\cdot t_e$$

For general interarrival and production times the approximation can be extended.

$$E\left[WT_{G|G|m}\right]=\left(\frac{c_a^2+c_e^2}{2}\right)\left(\frac{\rho^{\sqrt{2(m+1)}-1}}{m\cdot(1-\rho)}\right)\cdot t_e$$

For the exponential distribution $c_a = c_e = 1$, thus, this formula will lead back to the formula for the $M|M|1$ model.

5.1.2 Model assumptions

The arrivals of Tecnai and Titan are the arrivals of the columns. When these columns are available, and when an engineer becomes available, he can be assigned to one of the orders. At this moment the first in first out assumption is met by FEI.

The inter-arrival time and the production time follow a general distribution. The arrival rate is the number of orders that arrive in a certain period of time and the production rate is the number of orders that can be produced in the same period of time. Working overtime would cause fluctuations, as the production in two succeeding weeks can differ, due to over time. The queuing model can not deal with these fluctuations. However, it is allowed to assume that engineers work overtime one evening every week. If no orders are available the engineer can skip overtime and in busy periods, the overtime is used. This does not violate the constant capacity requirement of the model.

Another assumption of the model is, that all engineers are equal and, thus, capable of producing all orders. Section 4.3 shows that this is not the case and not necessary, since not all order require all skills. It is therefore not possible to use the queuing model for the different orders. Currently, the planning at FEI is such, that the assignment of engineers is not dependent on the skills of the engineers. When an engineer becomes available, he or she will be assigned to the first order in the queue. If the engineer is not capable of producing the entire order, a more experienced engineer will take over for the options the engineer can not perform. This causes waiting times, where the system waits for the experienced engineer and where the system of the experienced engineer waits for the return of the experienced engineer. This way of planning causes waiting times during production, not before production. The waiting times during production do cause engineer to be longer occupied, which indirectly effects waiting times before production. If the waiting times during production due to this way of planning are included in the production time of the system, the effect of this planning will be considered in the waiting times before production.

A last aspect to consider is the fact that most engineers of Titan used to be experienced engineers of Tecnai. Much knowledge, skills and overall capacity is passed from Tecnai to

Titan, leaving Tecnai with an undercapacity and a lack of experience. This requires Titan engineers to support Tecnai engineers in busy periods. This will modelled the same way as overtime. It will be assumed that Tecnai constantly has more capacity and Titan will constantly have less capacity during busy periods. However, since the busy periods of Tecnai and Titan will not necessarily occur at the same time, the decrease of capacity of Titan engineers will be less than the increase at Tecnai.

5.1.3 Validation waiting times

Using the queuing model described in section 5.1.1 and the assumptions of section 5.1.2, the expected waiting times can be determined. In the past year, the second half of 2007 and the first half of 2008, 33 TF20s, 7 TF30s, 3 Polaras, 22 Low Bases, 7 High Bases and 2 Krioses were produced. Using the mean and standard deviation of the production times found in section 4.1.3 and including the waiting times discussed in section 5.1.2, the average production time for Tecnai is 73,6 days and for Titan 103,0 days. The resulting coefficient of variance for Tecnai is estimated at 0,66 and for Titan at 0,43. On average the waiting times before production were 13,0 days for Tecnai and 24,9 for Titan.

All inter-arrival times and production times follow a general distribution and the $G|G|m$ queuing model will therefore be used.

During the past year, on average 15,25 engineers were available for Tecnai and 17,5 for Titan. After a discussion with the production manager at FEI, it became clear that only a third of the engineers worked overtime and a maximum of only 6 hours per 40-hour-workweek. This is thus a 5% increase in capacity. Assuming an engineer works 205 days a year (excluding national holidays, engineer's days off and illness), the average amount of workdays of each engineer, including overtime, would become 215 days. Furthermore, the assumption is made that, if necessary, the capacity of Tecnai engineers will receive a 10% increase from the capacity of Titan. As stated earlier, this will not have the opposite effect on the capacity of Titan, due too partly other busy times. It will therefore be further assumed that the capacity of Titan will decrease by 5%. This is approximately an increase of 1,5 engineers for Tecnai and a decrease of 0,9 engineers for Titan.

This production and these assumptions resulted in a utilization of respectively 88% and 92% for Tecnai and Titan. The $G|G|m$ model determines the average waiting times for Tecnai and Titan at 13,7 and 24,0 days respectively. These values can be considered a good approximation for the actual values of 13,0 and 24,9.

5.1.4 Expected waiting times

The desire of FEI is to train their engineers such that Tecnai engineers can completely produce the load of Tecnai systems and the same for Titan. By cross-training the engineers, the engineers will be able to produce entire orders, without creating extra waiting times because orders have to wait for an engineer with the proper skills. This would allow the use of the model with all engineers working only within their own team and with only 205 workdays every year. The waiting times for order shifts between engineers, will no longer need to be included.

For the production of the orders planned in the buildplan, 20 engineers for Tecnai are needed and 23 for Titan. More engineers will ensure shorter waiting times. The expected waiting times versus the number of additional engineers is shown in figure 11.

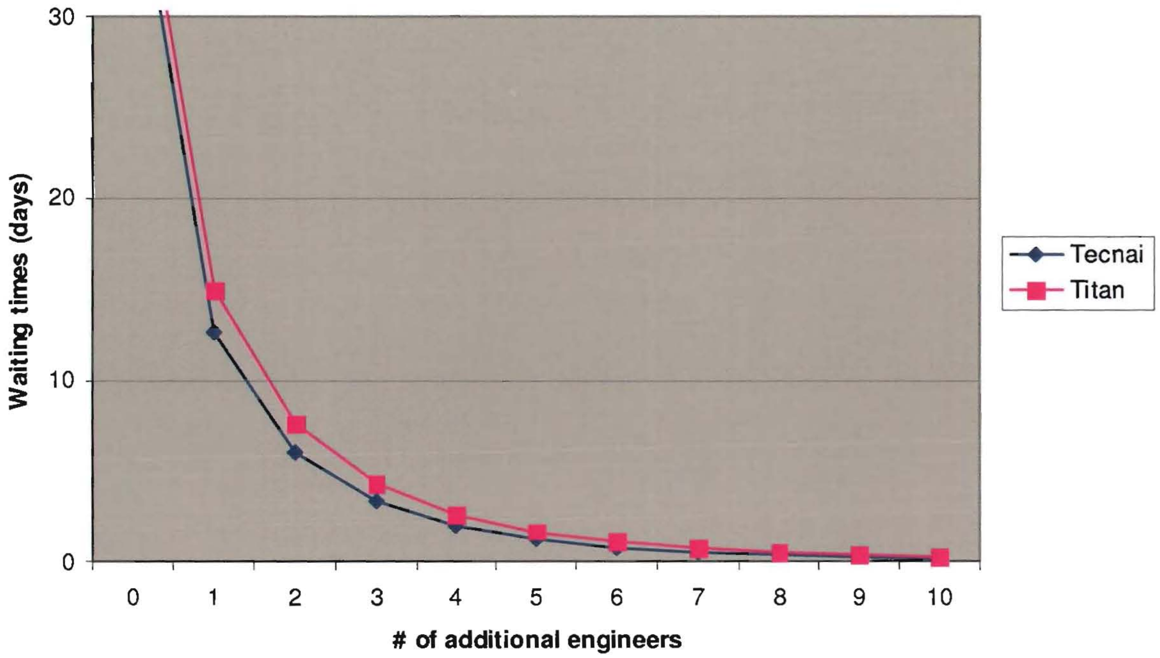


Figure 11: Expected waiting times for Tecnai and Titan

An engineer casts approximately €50.000,- per year. In section 4.1.2 it was already shortly discussed that waiting costs €75.000,- per week, thus €15.000,- per day. That means that an additional engineer is interesting if the engineer reduces the average waiting time by at least 3,3 days. For both Tecnai and Titan it would thus be wise to hire 3 additional engineers.

Queuing theory assumes that all engineers are equal. How the number of engineers will effect the waiting times when the skill matrix is not fully filled, will be further assessed using the planning tool, in section 6.3.

5.2 Skill matrices

The engineers at FEI are capable of performing different tasks by obtaining skills through training. Each engineer has different skills and each order requires different skills. It is possible to have a set of engineers for each type of order. However, the skills required for orders, described in the order-configuration, may fluctuate over time. It requires many engineers to ensure enough capacity is available, even when a certain skill is required more than usual.
FEI has chosen to cross-train their engineers, allowing engineers to perform different order configurations. Through cross-training the engineers receive training to perform different tasks, so that they may produce more different microscopes. This way it becomes easier to respond to the changing demands of the customers.

5.2.1 Literature cross-training

The cross-training at FEI is a special case. Where some companies can use chaining or reciprocal pairs (Inman et al., 2005), FEI requires cross-training closely resembling hierarchical cross-training. This means that the skills of an engineers are determined in a great extend to his experience (Gel en al., 2007). And more importantly, some engineers are required to have multiple skills in order to fulfil an order, instead of needing one or another skill. New engineers are only trained to produce a basic microscope, while more experienced engineers can be trained further to be able to add different options.

With hierarchical cross-training the skills of any two workers, described by the sets W_1 and W_2, satisfy one of the following criteria (Gel et al., 2007):

- $W_1 = W_2$;
- $W_1 \subset W_2$ or $W_2 \subset W_1$; or
- $W_1 \cap W_2 = \varnothing$

Emmons & Burns (1991) even use a simpler definition of hierarchical cross-training, where workers are ranked to be a type *k* worker and $W_1 \subset W_2 \subset ... \subset W_k$ describe the set of skills of workers of type 1 through *k*. The definition allows for two workers to be equal (the same type of worker), but does not allow workers to be completely different.

Hierarchical cross-training is still rather new in literature. Gel et al. (2007) show significant benefits of hierarchical cross-training in serial production. Emmons & Burns (1991), Narasimhan (1996) and Billionnet (1999) have created models to determine an optimal schedule when dealing with hierarchical cross-training. They used the workload of each level worker rather than proposing a model for a serial or parallel production environment.

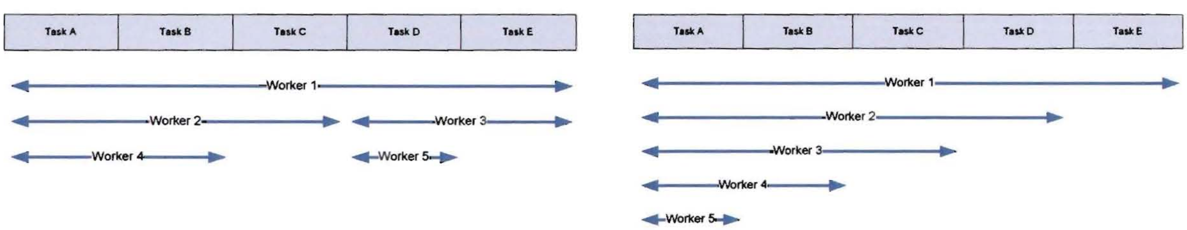
Emmons & Burns (1991) start by computing the required daily workforce. The decision for the schedule is partly determined by the assumption that type 1 workers are more expensive than type 2 workers and type 2 workers more expensive than type 3 workers, etc, due to higher salaries for more trained workers. The formulas work from top to bottom, as a result the most qualified workers are scheduled if not necessary. Salaries are not a consideration for this thesis, but this way of thinking does ensure minimal training to meet desired production, which is a cost issue for FEI.

5.2.2 Alterations

The reason why the current skill matrix only resembles hierarchical cross-training is that there is a set of basic skills learned in a specific order, but the skills for the further options do not require a specific order. This means it is possible that

$W_1 \subset W_3$ and $W_2 \subset W_3$,
but
$W_1 \neq W_2$ and $W_1 \not\subset W_2$ nor $W_2 \not\subset W_1$

Thus in stead of cross-training hierarchies as shown in figure 12, the cross-training is rather more like shown in figure 13.



a) Get el al. (2007) **b) Emmons & Burns (1991)**
Figure 12: Hierarchical cross-training

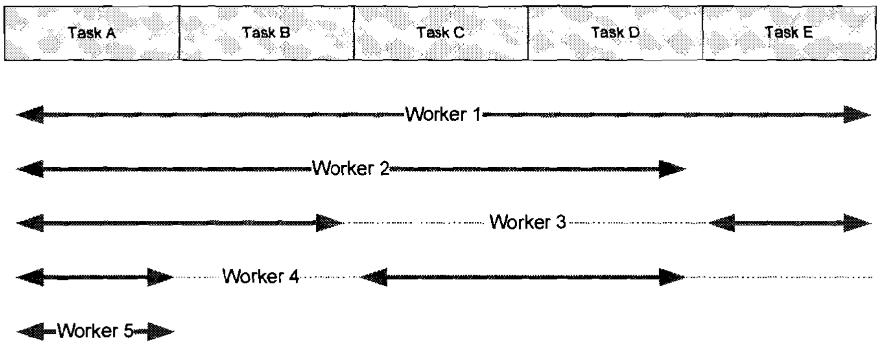


Figure 13: Hierarchical cross-training at FEI

The formulas of Emmons & Burns (1991) were designed in order to minimize the number of highest level workers. However, in the case at FEI, it may make more sense to train another worker 1 in order to decrease the necessity of workers 2 and 3 both by one, and thus minimizing the total workforce. Minimizing the number of highest level workers could also be translated in minimizing the worker that higher workers perform under their level. A constraint is needed to ensure that the total number of engineers does not exceed the required engineers determined by the queuing model of section 5.1. Therefore the following IP-model is proposed to determine the cross-training at FEI:

Parameter :	
R_i	= number of (parttime) engineers required to produce for skill set i
P_{ij}	= binary variable indicating if skill set j is a subset of skill set i
N_{tot}	= total number of engineers
Decision variables :	
N_i	= number of engineers with skill set i
A_i	= number of (parttime) engineers assigned to produce for skill set i
C_{ij}	= number of (parttime) engineers with skill set i producing for skill set j

$$\min \quad \sum_{i,j} C_{ij} \cdot P_{ij}$$

$$s.t. \quad A_i = N_i + \sum_j C_{ji} \cdot P_{ji} - \sum_j C_{ij} \cdot P_{ij} \qquad \forall i$$

$$A_i \geq R_i \qquad \forall i$$

$$\sum_i N_i = N_{tot}$$

$$N_i = \text{int} \qquad \forall i$$

$$C_{ij} \geq 0 \qquad \forall i, j$$

5.2.3 Skill sets

For Tecnai there are 4 skills for which the training needs to be determined: camera, gif, stem and edax. Other skills of Tecnai are basic skills and need to be mastered by all engineers. Furthermore, some combinations of accessories do not occur. This reduces the number of skill sets needed. The order configurations of the past 59 Tecnai systems results in the graphic representation of the skill sets in Figure 14.

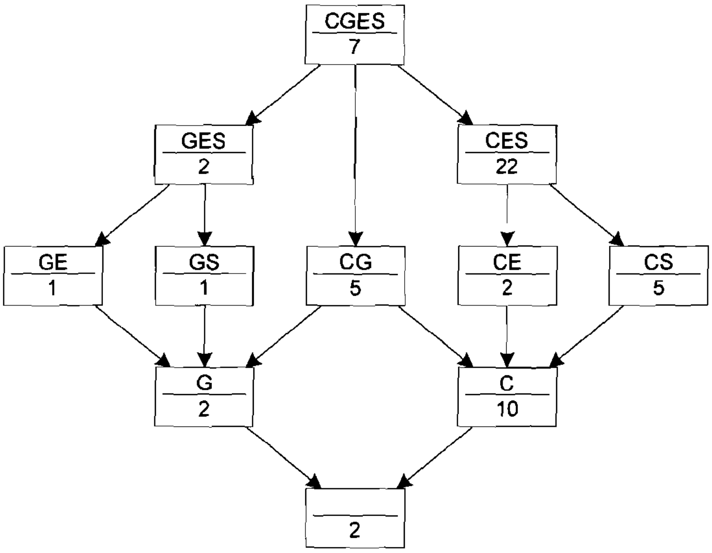


Figure 14: Hierarchical skill sets of Tecnai

The letters in the figure above indicate the skill required for the production of the order, the numbers indicate the number of Tecnai systems of the total of 59 systems follow this order configuration. As the figure shows, there are no orders for a Tecnai system and only stem or edax as accessories. Therefore, there is no need to train an engineer for these steps if the engineer is not trained for the accessories camera or gif. Using the average production times per step, the average production times and the required engineers for each step can be calculated. These requirements are the R_i of the LP-model and the possible skill sets are the sets shown in figure 14.

5.2.4 Stochastic orders

What the model in the previous section and the model of Emmons & Burns (1991) fail to reckon with, is the stochasticity within the requirement. Emmons & Burns' model (1991) is meant for a deterministic number of engineers needed each day. Since they are planning the workforce for the foreseeable future, the required workforce is known. For FEI the situation is somewhat different. As stated in the beginning of section 5.2, if a skill set is required more than usual, more engineers are needed and the LP-model for determining the skill matrix is lacking. The desired skill matrix can be determined by trial and error, using the results of the LP-model as a starting point. By assessing which engineers are most often idle and which orders experience the most delay, changes in the skill matrix can be determined.

5.3 Dynamic Assignment Algorithm

The operational solution should find a production schedule that meets certain requirements. The schedule should reckon with the skills and vacation days of an engineer. The schedule should ensure that as many orders as possible remain within the planned quarter and that columns are not too long stored, before orders are started.

5.3.1 Literature dynamic assignment

The situation at FEI is too complex to use a linear or non-linear programming model for the scheduling. Especially, since FEI has requested to program the model in MS Excel or Access. The solver of Excel can only deal with up to a 200 decision variables (according to Microsoft

Technical Support). Furthermore, since the arrival and production times are not deterministic and orders do not always have a constant configuration, assignment of orders to engineers should be dynamic, updating the schedule when new information becomes available.

Dynamic assignment problems use contributions or costs to assign orders or tasks to resources at the highest contribution or lowest cost. These type of problems would be a good alternative to linear programming problems. The use of contributions or costs allows a broad use of the problem, as users can define the basis of their decision to their own wishes. For instance, Wayne (1977) and Xu et al. (1992) have used dynamic assignment to assign customers to server queues, based on server capabilities and customer attributes. Corry & Kozan (2006) assign containers to free slots on a train, based on the weight distribution on the train and the number of actions to be taken. Grossmann et al. (1995) use dynamic assignment to assign stock to a storage location and Mahar et al. (2007) use the model to decide which storage location could best fulfil an online order, based on holding cost, transportation costs and current inventory. Sennot et al. (2006) schedule cross-trained floating workers in serial production, based on holding costs and setup-times and costs. Fleischmann et al. (2004) and Le Blanc et al. (2006) use dynamic assignment to assign transportation jobs to vehicles, based on travel distance, deliver time and vehicle capability.

What these models have in common, is that all these models are myopic, or shortsighted. When making an assignment, these models only consider the orders or tasks and resources to be assigned during the current period. It ignores information on future orders and resources until the information appears in the current period. This may be interesting if information of future orders and resources is scarce or if only the next assignments are of interest. In these cases a longer period may be chosen in order to asses if a resource or order should be assigned immediately or later. The advantage of this way of planning is that it takes only seconds to create a new schedule. However, for FEI it is interesting to look further ahead, so that they may use the information from the model to set a due date for orders. It is not possible to include all orders and resources to a myopic model at once, because the availability of the engineers is determined by the decision to assign. Therefore, shorter periods are necessary and resources have to be assigned immediately or myopic models are insufficient.

Spivey & Powell (2004) introduce a non-myopic model for dynamic assignment. Their dynamic assignment algorithm allows the scheduling of current orders and resources while reckoning with future orders and resources. Since the algorithm assigns all orders and forecasted orders within the time horizon, new information can be processed by rerunning the algorithm. A distinction between the algorithm and the situation at FEI is that engineers in the algorithm disappear from the system once an assignment has been made. In reality the engineer will become unavailable for the duration of the production and then will become available once more. This means that the duration of an order has an effect on the availability of the engineer and thus on the contribution of an assignment. Alterations will be made to the model to accommodate for this.

A downside of the model of Spivey and Powell (2004) is that a run of the algorithm will take 10 to 30 minutes, depending on the number of iterations and the speed of the computer. However, when an engineer is becoming available, this can be foreseen a day in advance, leaving ample time to run the algorithm. It is expected that the algorithm will only be run once a week, before the progress meeting. Therefore, the run time is not an important factor for the decision of the model.

5.3.2 General model description

The dynamic assignment algorithm of Spivey & Powell (2004) is an interesting model for FEI. The assignment of orders to engineers is based on the attributes of both engineers as orders. The combination of these attributes creates a unique contribution for each possible assignment. For the dynamic assignment algorithm the following notations will be used:

r	= index for resources
l	= index for orders
t	= time period, t=0,...,T
k	= index for iteration
$\mathcal{R}$	= set of resources that may enter the system
$\mathcal{L}$	= set of orders that may enter the system
$\hat{R}_{tr}$	$= \begin{cases} 1 & \text{if resource } r \in \mathcal{R} \text{ becomes known in period } t \\ 0 & \text{otherwise} \end{cases}$
$\hat{R}_t$	= set of resources coming available at time t
	$= \left(\hat{R}_{tr}\right)_{r\in\mathcal{R}}$ (vector of $\hat{R}_{tr}$)
R_{tr}	$= \begin{cases} 1 & \text{if resource } r \in \mathcal{R} \text{ is known and available at time } t \\ 0 & \text{otherwise} \end{cases}$
R_t	= set of resources available at time t (vector of R_{tr})
$\hat{\mathcal{R}}_t$	$=\{r \mid \hat{R}_{tr}=1\}$
$\mathcal{R}_t$	$=\{r \mid R_{tr}=1\}$
similarly for $\hat{L}_{tl}$, $\hat{L}_t$, L_{tl}, L_t, $\hat{\mathcal{L}}_t$, $\mathcal{L}_t$	
$\mathbf{S}_t$	= state of the system at time t
	$=(\mathcal{R}_t, \mathcal{L}_t)$
x_{trl}	$= \begin{cases} 1 & \text{if resource } r \text{ is assigned to order } l \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$
c_{trl}	= contribution if resource r is assigned to order l at time t
x_t and c_t are the matrices of x_{trl} and c_{trl}	
$V_t(\mathbf{S}_t)$	= maximum contribution that can be achieved when in state $\mathbf{S}_t$
$\mathbf{X}\ (\mathbf{S}_t)$	= set of assignments
$\mathbf{X}_t^R$	= set of resources being assigned at time t
$\mathbf{X}_t^L$	= set of orders being assigned at time t
$C(\mathbf{S}_t)$	= contribution function given state $\mathbf{S}_t$
$C_r^+(\mathbf{S}_t) = C(\mathbf{S}_t \cup \{r\})$	for $r \notin \mathcal{R}_t$
$C_r^-(\mathbf{S}_t) = C(\mathbf{S}_t - \{r\})$	for $r \in \mathcal{R}_t$
$C_{rl}^+(\mathbf{S}_t) = C(\mathbf{S}_t \cup \{r\} \cup \{l\})$	for $r \notin \mathcal{R}_t$, $l \notin \mathcal{L}_t$

$\hat{v}^k_{tlr}$	= the estimation of the value of resource r and order l at time t obtained directly in iteration k
$\bar{v}^k_{tlr}$	$= \alpha^k \hat{v}^k_{tlr} + (1-\alpha^k)\bar{v}^{k-1}_{tlr}$ (smoothed $\hat{v}^k_{tlr}$)
α	= smoothing constant

Dynamic programming often uses a technique of working backwards through the solutions. Starting at the end and working to the beginning decreases the number of solutions to consider immensely. In stead of considering all possible solutions, the best solution of the states in the last period is determined. When determining the last solution for the period before, the contribution of the decision is added to the contribution of the resulting state. Since the contribution of the resulting state is already optimized, the maximum of the sums will be an optimal. This is continued until the first period. With a scenario where there are 3 periods and for each period two choices, there are $2^3 = 8$ possible solutions, with each 3 calculations, thus a total of 24 calculations. Using dynamic programming only12 calculations are needed. This difference is still very small, but if the situation occurs that 5 options can be chosen every period for 5 periods, $5^5 \cdot 5 = 16$ thousand calculations are needed without dynamic programming and only 105 calculations using dynamic assignment. (Winston, 2004)

The assignment algorithm is based on dynamic programming. For each decision it considers the value of the state in which the system will be in after the decision. The value that can be obtained from a certain state can be defined in the following value function:

$$V_t(\mathbf{S}_t) = \begin{cases} \max\left\{c_t \cdot x_t + E\left[V_{t+1}(\mathbf{S}_{t+1}) \middle| \mathbf{S}_t\right]\right\} & t = 0,\dots,T \\ 0 & t = T+1 \end{cases}$$

In order to simplify the formula, the following alternative function has been suggested by the authors:

$$\tilde{V}_t^{rk}(\mathbf{S}_t) = \max_{x_t}\left\{\sum_{r\in\mathcal{R}}\sum_{l\in\mathcal{L}}\left(c_t - \bar{v}^{k-1}_{t+1,rl}\right)\cdot x_t\right\}$$

For the derivation of this function, please refer to Spivey & Powell (2004).

The value of an order or engineer is determined by comparing a state where the order and task are available with a state where both are no longer available. For the value of a certain state, the static assignment problem described by Spivey & Powell (2004) can be:

$$C(\mathbf{S}') = \max \sum_{r,l} c_{rl} \cdot x_{rl}$$

$$\text{s.t.} \quad \sum_{l\in\mathcal{L}'} x_{rl} \le \begin{cases} 1 & \forall r \in \mathcal{R}' \\ 0 & \forall r \notin \mathcal{R}' \end{cases}$$

$$\sum_{r\in\mathcal{R}'} x_{rl} \le \begin{cases} 1 & \forall l \in \mathcal{L}' \\ 0 & \forall l \notin \mathcal{L}' \end{cases}$$

$$x_{rl} \in \{0,1\} \qquad \forall r \in \mathcal{R}, \forall l \in \mathcal{L}$$

Algorithm

The algorithm is setup in order to determine $\overline{v}_{t+1,rl}^{k-1}$ and x_t for all periods, orders and engineers.

Step 0: Determine a maximum number of iterations *K*. Set $\hat{v}_{trl}^{k}=0$ and $\overline{v}_{trl}^{k}=0$ for all *r*, *l* and *t*. Set $k=1$ and $t=0$.

Step 1: For the current *k* and *t*, solve the assignment problem

$$\tilde{V}_t^{rlk}(\mathbf{S}_t)=\max_{x_t}\left\{\sum_{r\in\mathcal{R}}\sum_{l\in\mathcal{L}}\left(c_{trl}-\overline{v}_{t+1,r}^{k-1}\right)\cdot x_{trl}\right\}$$

$$\text{s.t.}\qquad \sum_{l\in\mathcal{L}}x_{trl}\le\begin{cases}1 & \forall r\in\mathcal{R}_t\\ 0 & \forall r\notin\mathcal{R}_t\end{cases}$$

$$\sum_{r\in\mathcal{R}}x_{trl}\le\begin{cases}1 & \forall l\in\mathcal{L}_t\\ 0 & \forall l\notin\mathcal{L}_t\end{cases}$$

$$x_{rl}\in\{0,1\}\qquad \forall r\in\mathcal{R},\forall l\in\mathcal{L}$$

Step 2: Once the argmax x_t in step 1 is determined, let $\mathcal{R}_{t+1}=\mathcal{R}_t+\hat{\mathcal{R}}_{t+1}\text{-}\mathbf{X}_t^{\;R}$ and $\mathcal{L}_{t+1}=\mathcal{L}_t+\hat{\mathcal{L}}_{t+1}\text{-}\mathbf{X}_t^{\;L}$.

Step 3: If $t<T$ then $t=t+1$ and go to step 1.

Step 4: Let N_t be the network consisting of all resources and tasks available at iteration *k* and times $t'\ge t$. Then, for the current *k* and *t*, and for each *r* and *l* that are available at time *t* (even one or both were assigned before time *t*), calculate $\hat{v}_{trl}^{k}$ according to one of the following cases.

$$\hat{v}_{trl}^{k}=\begin{cases}C(N_t)-C_{rl}^{-}(N_t) & \text{if both } r \text{ and } l \text{ are available at time } t\\ C_{rl}^{+}(N_t)-C(N_t) & \text{if neither } r \text{ and } l \text{ are available at time } t\\ C_r^{+}(N_t)-C_l^{-}(N_t) & \text{if } r \text{ is available at time } t \text{ and } l \text{ not}\\ C_l^{+}(N_t)-C_r^{-}(N_t) & \text{if } l \text{ is available at time } t \text{ and } r \text{ not}\end{cases}$$

Step 5: For each *r* and *l*, set $\overline{v}_{tlr}^{k}=\alpha^k\hat{v}_{tlr}^{k}+\left(1-\alpha^k\right)\overline{v}_{tlr}^{k-1}$.

Step 6: If $t>0$, then $t=t-1$ and go to step 4.

Step 7: If $k<K$, then $k=k+1$ and go to step 1; otherwise stop.

5.3.3 Alterations to the model

The model requires a few alterations in order to better fit the situation of FEI. The alterations are related to the calculation of the estimated future values and to some of the assumptions made.

Future value

The first alteration is already implemented in the algorithm. Spivey & Powell (2004) had only considered the future value of an engineer for their decision, but also suggested an alteration in which the future value of both the engineer and orders is considered. This alternative is used in the algorithm above, since it may be interesting to postpone an order as well as an engineer.

Availability of the engineer

Spivey & Powell (2004) assume that every order and engineer is assigned only once and will leave the system after the assignment. However, the engineers at FEI become available again once the order is finished. Thus, an assignment affects the availability of the engineers. Since not all periods are planned at once, it is important to include this availability in the future value.

There are three different ways to include the availability in the future value:

- **Minimize down time:** dummy orders could be included. If an engineer is not assigned to a real order, an assignment will be made to a dummy order. The engineer will not be eliminated from the system with such an assignment, but the assignment will result in a negative contribution. This way the down time of an engineer is minimized. This method is used by Fleishmann et al. (2004).
- **Earliest due date:** it is possible to include the due date of an order in the contribution. An earlier due date would lead to a higher value, regardless of the requested delivery date of the order.
- **Include more future values:** the value that the engineer could achieve in the assignment after the due date of the current assignment can be included in the future value of the engineer. This is the solution that best fits the formula for $V_t(\mathbf{S}_t)$, for it actually includes the information of all future states the engineer is in.

The method used for the situation at FEI will be a combination of the first two options. With a utilization rate of 80%, letting an engineer wait for 4 periods, will already jeopardize the production rate. The first option should help counteract this. However, Fleishmann et al. (2004) use a different model where dummy orders are possible, In the current model, it is possible to make no assignment. Therefore, a contribution will be used to encourage fast assignment.

The second option should help if a trade off has to be made between different assignments that are close after the moment the engineer and order become available. By creating a contribution that encourages high trained engineers to become available as soon as possible, future contributions should be higher.

The last option is difficult to model. Furthermore, the due date is an estimation. If this due date changes, the future values may change significantly.

Calculating future value

The last alteration of the model is partly due to the prior alteration. Because engineers reappear into the model after some time, the future value should not be calculated for all orders and engineers in the future. The future value calculated in step 4 of the algorithm, will only calculate the value for the orders and engineers appearing x periods in the future. This will have two effects. Orders and engineers that have not been assigned in the x periods after arrival, will automatically receive a higher chance of being assigned. But most importantly, this makes the calculation of this value possible for excel to calculate. If this limitation was not made, the calculation in the first period would include all orders and engineers known at that moment, which would be much more than 100 decision variables.

The new version of step 4 should be:

Step 4: Let N_t be the network consisting of all resources and tasks available at iteration *k* and times $t - x \geq t' \geq t$. Then, for the current *k* and *t*, and for each *r* and *l* that became available in the x periods before time *t* (even one or both were assigned before time *t*), calculate $\hat{v}^k_{trl}$ according to one of the following cases.

5.3.4 Contribution

Spivey & Powell (2004) speak of unique attributes on which the contribution can be based. There are several factors that affect the contribution of the assignment of an order to an engineer. First of all, the engineer needs to be capable of producing the order to which he is assigned, either with training or without. Second, the waiting times should be minimized. In order to translate these factors into contributions, a set of attributes for both the engineers and the orders are proposed. Let a_r be the vector of attributes of engineer *r* and let b_l be the vector of attributes of order *l*.

For the Tecnai production group the proposed attributes of engineer *r* and order *l* are:

$a_{r,t}$	$= \{t \mid \hat{R}_{tr} = 1\}$	$b_{l,t}$	$= \{t \mid \hat{L}_{tr} = 1\}$
$a_{r,tr}$	$= \{1,...,12\}$ last received training	$b_{l,eq}$	= end of delivery quarter order *l*
$a_{r,1}$	$= (0,1)$ level of plug in	$b_{l,1}$	$= \begin{cases} 1 \text{ if plug in is required} \\ 0 \text{ otherwise} \end{cases}$
$a_{r,2}$	$= (0,1)$ level of column test	$b_{l,1}$	$= \{0,1\}$ for column test is requirement
$a_{r,3}$	$= (0,1)$ level of optic test	$b_{l,2}$	$= \{0,1\}$ for optic test requirement
$a_{r,4}$	$= (0,1)$ level of HOV	$b_{l,3}$	$= \{0,1\}$ for HOV requirement
$\vdots$		$\vdots$	
$a_{r,11}$	$= (0,1)$ level of dismantling	$b_{l,12}$	$= \{0,1\}$ for dismantling requirement

These attributes are already linked to each engineer and the order. Progress files predict the period the engineers will become available ($a_{r,t}$) and the skill matrix denotes at which level the engineers can perform a certain skills, including the last training received ($a_{r,j}$ and $a_{r,tr}$). For the orders, the current planning shows when a column arrives and production can start ($b_{l,t}$), in which quarter the order should be delivered ($b_{l,eq}$) and what the order configuration will be ($b_{l,j}$).

Possible assignments

The algorithm should not assign an order to an engineer that is not capable of producing that order, even after training. Therefore, the contribution should be extremely negative to ensure this assignment is never made. Let *j* be the index for a task (0,...,11) and let $Tr_{r,j}$ be the binary decision to train engineer *r* on task *j*. Training is only possible for tasks where $a_{r,j} = 0$ and if the engineer has mastered the last skills he trained for, thus if $a_{r,a_{r,tr}} = 1$. After training the level of the trained skill will be α. An engineer can improve this level through experience.

Let $TN_{r,l}$ be the number of trainings needed, resulting in the possibility of the assignment $AP_{r,l}$.

$$TN_{r,l} = \sum_{i=1}^{11} \{1 | b_{l,i} = 1 \cap a_{r,i} = 0\}$$

$$AP_{r,l} = \begin{cases} 1 & \text{if } TN_{r,l} = 0 \\ 1 & \text{if } TN_{r,l} = 1 \text{ and } a_{r,a_{r,tr}} = 1 \\ 0 & \text{otherwise} \end{cases}$$

The basic contribution for each assignment will be determined by the possibility of the assignment. Let $\not{c} = -\infty$ be the contribution of all undesirable assignments and let $c^{+} = 10$ be the contribution for a possible assignment.

$$c_{AP} = \begin{cases} c^{+} & \text{if } AP_{r,l} = 1 \\ \not{c} & \text{if } AP_{r,l} = 0 \end{cases}$$

The rest of the contributions only need to be determined if $AP_{r,l} = 1$.

Early assignment

In order to minimize the waiting times, the orders need to be assigned as soon after the arrival of the column as possible and engineers should be as little idle as possible. Therefore, both engineer and order receive a contribution that is higher for engineers and orders becoming available earlier.

$$c_r = T - a_{r,t}$$
$$c_l = T - b_{l,t}$$

Because of these contributions, an early assignment of engineers and orders will become more interesting.

Training and experience

In some cases training is needed before an engineer is capable of producing an order. As stated earlier, this is denoted by $TN_{r,l} = 1$. These trainings will be assigned automatically if not enough engineers are available with the required skill set. When training has been followed, the engineer should gain more experience by performing the task more often, until the skill is fully mastered. This improves the learning process and will allow the engineer to receive further training later on if needed.

Let a desired experience be noted by the binary variable $DE_{r,l}$.

$$DE_{r,l} = \begin{cases} 1 & \text{if } TN_{r,l} = 0 \text{ and } a_{r,a_{r,tr}} < 1 \\ 0 & \text{otherwise} \end{cases}$$

Let $c_{exp} \cdot DE_{r,l}$ be the contribution received for gaining experience. The height of this contribution affects the choice between early assignment and gaining experience. If the contribution would be 2, the desired experience would allow for 2 more weeks delay for another order.

Total contribution

The total contribution is determined by the possibility of the assignment, the arrival of engineer and order and the desired experience gained, resulting in a contribution for possible assignments:

$$c_{tot} = c^{+} + c_r + c_l + c_{exp} \cdot DE_{r,l}$$

This contribution should be calculated for every combination of *r* and *l* and for every time period.

In the next chapter the desired skill matrix and this tool are set to the test, in order to assess if these solutions will actually benefit FEI.

Part III Implementation

6. Results

In this chapter the results generated by the dynamic assignment tool will be discussed. The results will be compared to a simplified model of current planning. This simplification can be justified by the fact that the simplification occurs in both models. These simplifications in both models are the assumption that engineers all take the same vacations; engineers of Titan do not help out in busy periods of Tecnai; and no overwork is allowed.

The results will be compared for different scenarios. Therefore, this chapter will start in the first section by defining these scenarios. After that, a short description will be given as to the method with which the model parameters were determined. The simplified model is discussed in section 6.1.2 and the results of both models will be compared in the following sections of this chapter.

6.1 Test environment

6.1.1 Scenarios

Order sets

In the build plan of October 39 TF20 systems and 9 TF30 systems are planned for production. These numbers are used in the tests with this tool. Using historical data on order-configurations, three different order sets were created. Each of these set had slightly different set of order-configurations and these configurations were all in a different order.

Skill matrix

For the 46 Tecnai systems to be scheduled, at least 14 engineers are needed, resulting in 99,6% utilization. Using queuing theory, the desired number of engineers (based on the trade-off between the number of engineers and waiting times) is 17 engineer. Currently, the Tecnai team consists of 17 engineers, resulting in a utilization of 82%. Using the model of section 5.2 a skill matrix was determined that would be used as a starting point for the final skill matrix. The skill matrix was updated somewhat before the first run, because the resulting skill matrix allowed for some engineers to be trained for only one or two orders. This would result in an expected utilization of that engineer of as low as 20%. These alterations resulted in the skill matrices shown in figure 15, where the coloured cells indicate the skills that need to be learned.

ma	fc	of	hf	ac	ca	gi	ed	st	ad	CSM	SMM	SM+1	SM+2	SM+3
										3	2	2	3	4
										10	6	8	8	8
										0	2	2	1	1
										0	0	0	0	0
										0	0	0	0	0
										0	2	2	2	2
										0	1	1	1	0
										0	2	2	2	2
										2	2	0	0	0
										0	0	0	0	0
										2	0	0	0	0
Number of additional skills needed										44	44	48	49	51

Figure 15: Skill matrices

The schedules were compared for the skill matrices in figure 15: the current skill matrix (CSM), the skill matrix from the training model (SMM) and further improved skill matrices (SM+). The further improved skill matrices were determined by checking the results of the dynamic assignment tool. Engineers that were assigned very little, average over the three order sets, were upgraded to possess skills of the orders experiencing the longest waiting times. The results are shown in section 6.2.

Stochastic production times

The models were tested for different production times. First, each order set was run for deterministic production times, based on the averages noted in Appendix C. In section 4.1.3 it was assumed that the production times are normally distributed with regard to the expected production times. Therefore, the model was checked with normally distributed production times. The production times were updated every week and the algorithm was rerun after every update to determine the new schedule.

The start up was such that all engineers were assigned at the beginning of the planning horizon. As the assignment lies in the past, it is known for certain. For each of the engineers a stochastic production time was set and the arrival time of the engineer was also updated every period.

6.1.2 Current planning

In the current planning model, an arriving order is assigned to the first engineer that becomes available. If this engineer is capable of the entire order, he completes the order and is assigned to a new order. If the engineer can not complete the order, he will work on it as long as possible, after which the engineer is assigned to another order and the order becomes available once more. The engineer that takes up an uncompleted order must be able to complete it.

6.2 Skill matrix

The first tests were done to compare the different skill matrices using the model for current planning, the dynamic assignment algorithm with both 1 iteration, thus without any future value, and with 3 iterations. The choice of 3 iterations was made because results showed that

3 iterations rendered better results than 2 iterations and approximately the same results as 4 iterations. After 4 iterations, the results did not change at all.

The results are specified in Appendix A. The results are summarized in table 8, by reviewing the average results of the three order sets.

		CSM	SMM	SM+1	SM+2	SM+3
CP	# orders assigned	34,7	31,7	34,0	35,3	36,3
	# orders within quarter	29,7	26,7	28,7	31,0	32,3
	average waiting times	3,1	3,3	3,1	2,8	2,7
DA k=1	# orders assigned	41,7	40,7	41,7	42,7	43,3
	# orders within quarter	35,0	31,0	35,3	39,7	40,0
	average waiting times	3,4	4,0	3,0	1,9	1,7
DA k=3	# orders assigned	41,7	41,7	42,7	43,0	43,3
	# orders within quarter	37,0	34,0	37,0	39,0	40,3
	average waiting times	2,8	3,5	2,7	2,2	1,7

Table 8: Results comparison skill matrices

The reason why the summarized results are used is that the order configurations affect the results. If a specific configuration occurs more than often within a time interval, the waiting times may increase due to that occurrence, instead of the chosen skill matrix.

For all planning models, the results of the current skill matrix are approximately the same to the results of SM+1. The current skill matrix requires less training and is therefore more interesting. However, in the current skill matrix, two engineers have not yet learned any addition skills. This meant that these engineers were each assigned to only one order in the entire year. SM+2 and SM+3 deliver better results than all other skill matrices.

The results show that dynamic assignment benefits most from SM+2 and SM+3. In dynamic assignment, an order waits for an engineer that is capable of producing the order. More filled skill matrices will ensure that it is more likely that the next arriving engineer is capable of the order. In the current planning it becomes more likely that the first engineer is capable of the entire order and waiting times during production will decrease, but as there are both waiting times before the order as after the order, the total waiting times decrease less than for the other planning models. The better filled the skill matrix; the less benefit can be gained from dynamic assignment. The iterations are needed to ensure that a highly trained engineer is not assigned to an easy order this week, while an engineer with fewer skills is left with an order he is not capable of. However, if most engineers are capable of most orders, this problem will occur less often.

The waiting times of the current planning may appear practically equal to the waiting times of dynamic assignment, there is a difference. Both models of dynamic assignment perform considerably better concerning the number of orders started by the end of the year and the number of orders finished within the planned quarter. Under the current skill matrix, the current planning was able to assign only 34,7 orders within the year, while both dynamic assignment models assign 41,7 orders, a difference of 7 orders out of the 11,3 orders current planning missed. For the orders within the quarter for dynamic assignment without and with iterations, the difference was respectively 5,3 and 7,3 orders out of the 16,3 orders missed by current planning.

The waiting times are only of the orders assigned. The orders not assigned are the orders that arrived last. The arrivals were set up to be linear and it can therefore be assumed that the last 10 orders not assigned have an average of 5 weeks waiting time at the end of the planning horizon at which time they were not yet assigned. These waiting times were not included in the waiting times in table 8, because the waiting times are not yet certain. If it these waiting times were used, the current skill matrix would have an average waiting time of 3,1 for the 34,7 assigned orders and at least 5,65 for the 11,3 unassigned orders. This would results in an average waiting time of at least 3,7. Calculating the same minimum waiting times for the other cases, dynamic assignment (thus with iterations) improves the waiting times by 28% for CSM, 25% for SMM, 32% for SM+1, 36% for SM+2 and 46% for SM+3.

The model using dynamic assignment without iterations is basically current planning, but not allowing engineers to partially produce an order. The improvements in waiting time dynamic assignment shows over de model without iterations are mainly seen for skill matrices that are less filled. For better filled skill matrices, the difference is much lower.

6.3 Workforce

The assessment of the workforce is done on several levels. First of all the sensitivity of the skill matrix is determined by assessing the loss of one of the fully trained engineers. Second the schedule is determined for models with different number of engineers.

6.3.1 Losing an engineer

The results of the runs of the dynamic assignment tool are shown in table 9.

		CSM	SMM	SM+3
Order set 1	# orders assigned	42	39	43
	# orders within quarter	37	29	36
	average waiting times	4,2	5,2	3,5
Order set 2	# orders assigned	39	40	42
	# orders within quarter	35	32	39
	average waiting times	3,4	3,7	2,1
Order set 3	# orders assigned	37	40	41
	# orders within quarter	32	34	37
	average waiting times	2,9	3,2	2,2
Average	# orders assigned	39,3	39,7	42,0
	# orders within quarter	34,7	32,7	37,3
	average waiting times	3,5	4,0	2,6

Table 9: Results after loss of engineer

Comparing these results to the results for dynamic assignment in table 8, the schedules perform worse. CSM has more highly trained engineers, which makes it more resilient to the loss of one of them. But the least affected is schedule using SMM. With 17 engineers, orders can be assigned to an engineer more trained than needed, to avoid long waiting times, if SM+3 is used. When using the SMM is used, highly trained engineers are used mostly for difficult orders. Extracting a highly trained engineer, will therefore affect more orders if SM+3 is used, than for SMM. This might explain why extracting a highly trained engineer affects SM+3 the most.

6.3.2 Different workforce sizes

In section 5.1.4 the trade-off was made between holding costs and the cost of hiring an engineer. With the 46 orders used in the order sets, 17 engineers was suggested using queuing theory. The effect of the number of engineers on the waiting times was assessed using the dynamic assignment tool. For 17 engineers, SM+3 was already determined. For the other number of engineers assessed, the same alterations were made as to the SMM model. The results are shown in the table below. The table also shows the extra engineers and training required in comparison to the situation of 17 engineers.

		SMM	SM+3	Required engineers and training
15	# orders assigned # orders within quarter average waiting times	38,7 26,3 5,1	38,7 27,3 4,9	-2 engineers with 2 additional skills each
16	# orders assigned # orders within quarter average waiting times	39,7 31,0 3,9	43,0 39,3 2,7	-1 engineer with 2 additional skills
17	# orders assigned # orders within quarter average waiting times	41,7 34,0 3,5	43,3 40,3 1,7	see figure 15
18	# orders assigned # orders within quarter average waiting times	43,3 37,0 3,1	45,7 44,3 1,2	+1 engineer with 3 additional skills

Table 10: Results comparison different workforce size

The trade-off between holding cost and hiring another engineer suggests that an extra engineer is beneficial if the hiring of that engineer results in a reduction of waiting times by at least 0,7 weeks. If SM+3 is pursued, the dynamic assignment tool also suggests 17 engineers. If SMM is pursued, the 17th engineer does not reduce the waiting times enough to hire this engineer. The results in table 10 seem to show the waiting times decline at a slower pace for SMM than for SM+3.

The chosen skill matrix becomes more effective if more engineers are hired. This can be explained by the fact that the waiting times when using 15 engineers are mostly caused by the number of engineers and the waiting times when using 17 engineers are caused by the choice of the skill matrix.

This evaluation was made using production times with less variance. Only the variance due to different order configurations was included. However, if this variance of the production time was lowered, queuing theory still advised 17 engineers. Thus, queuing theory is still an interesting estimator for the required workforce given SM+3. The estimated waiting times differ from the results above, where the waiting times are strongly affected by the chosen skill matrix.

6.4 Stochastic production times

The results so far were all based on deterministic production times. However, dynamic assignment was chosen because of its ability to cope with stochastic information. Therefore, the tool was also tested on its ability to respond to new information. In section 6.1.1 it was already discussed how the stochastic production times were integrated into the model.

6.4.1 Using stochastic information in DA

The results are once again compared to the current planning. It is expected that the current planning will be little affected by stochastic production times, as the assignment of orders and engineers is not affected by these production times. Dynamic assignment, however, makes assignments, based on information of all orders and engineers becoming available in the near future. If an order is postponed for a more suitable engineer becoming available next week, while another engineer is capable of the order this week, the assignment is affected by stochastic production times. If the more suitable engineer becomes available later than expected, the tool may have made a different assignment if the arrival time was known earlier.

		CSM			SM+3		
		CP	DA (deter)	DA (norm)	CP	DA (deter)	DA (norm)
Order set 1	# orders assigned	40	43	44	40	45	43
	# orders within quarter	37	41	38	36	42	40
	average waiting times	2,9	3,1	3,5	2,9	2,2	2,4
Order set 2	# orders assigned	38	43	43	40	41	43
	# orders within quarter	36	38	33	37	40	37
	average waiting times	2,0	2,0	3,3	1,1	1,1	1,8
Order set 3	# orders assigned	34	39	37	36	44	42
	# orders within quarter	31	32	28	33	39	31
	average waiting times	2,1	3,2	3,0	1,8	1,9	2,2

Table 11: Results stochastic production times

Dynamic assignment still outperforms the current planning, but is affected by the stochastic production times. For some order sets, the results are even less. The effect of the stochastic production times are smaller for SM+3, because more engineers are capable of taking over an order if the production time is much longer than expected.

If we recall that the waiting times are also affected by the number of orders not assigned, the dynamic assignment tool improves waiting times by almost 10% under these stochastic production times. If the standard deviation can be reduced by FEI, dynamic assignment will give better results.

6.4.2 Due date prediction

One of the reasons why a non-myopic model was chosen is that a schedule can be made for orders in the future as well as current orders. This way a due date can be predicted. It may be interesting for FEI to make these predictions. FEI wants 90% of the orders to arrive before the due date set shortly after the arrival of the order. Using the distribution of the ratio of the production times to the expected production times, the distribution of the production time can be estimated. 90% on time delivery means that the due date should be set such that even if the production time increases by $1,3\sigma$, the order will still arrive. The schedule of dynamic assignment will show if immediate assignment is possible, given the current skill matrix and the configurations of other orders. If for instance an order is not assigned directly, but has to wait for a currently occupied engineer, the due date should be when that engineer has finished both orders, plus a safety lead time to ensure that the due date is not crossed with a certainty of 90%.

However, it is not necessary to secure a safety lead time of $1,3\sqrt{2\sigma^2}\cdot PT$, because if the production time of the first order is longer than expected, the second order may be taken over by another engineer. A safety lead time of $\sqrt{2\sigma^2}\cdot PT$ may be enough. This lead time should be higher than the safety lead time of $1,3\sigma$ for the order on its own. The same can be done for engineers performing four orders directly after each other. The due date prediction should be further worked out.

6.5 Training and experience

Another aspect that was not yet assessed in the previous sections is the training. Since the current skill matrix can not be transferred into SM+3, imagine a future situation where two engineers with the skills camera, edax and stem have left; that the two new engineers have mastered the skill camera; and that two new engineers have been hired and are trained only for the basic skills. Table 12 shows the results of the situation without training, the situations where training is given and the situation where all engineers are already trained according to SM+3. The table also shows the number of trainings given.

		No training	Training	#	Finished training
Order set 1	# orders assigned	40	43	8	45
	# orders within quarter	33	38		42
	average waiting times	4,5	3,7		2,2
Order set 2	# orders assigned	40	41	7	41
	# orders within quarter	32	36		40
	average waiting times	3,1	2,3		1,1
Order set 3	# orders assigned	37	40	7	44
	# orders within quarter	27	31		39
	average waiting times	4,1	2,8		1,9

Table 12: Results training

In order to transfer the skill matrix into SM+3, 11 trainings are needed. The first order set realised 8 trainings within the first year, the other order sets realised 7 trainings. Since the skill matrix is not yet as good as SM+3, the results are less. However, training does not reduce the results more than the results benefit from the training. The training is thus well implemented into the tool. It will determine when and which training is needed and the results benefit from the training.

7. Implementation

7.1 Buildplan decision using queuing theory

For buildplan meetings a calculation sheet in Excel was used to determine the number of slots for each type of system. In the orientation part the variables of this decision have been briefly discussed. Capacity information was not yet part of the decision process. In order to improve this situation, the calculation sheet was extended to include information on the total workforce. This information included the average utilization of the engineers, the probability that the buildplan could be met and the required buildplan decreases in order to create a buildplan that can be met. The tool also makes a suggestion for the required workforce, based on the queuing model of section 5.1.

It is important to keep the information of production times as up to date as possible. If the production process changes and as a result the production times change, these changes should be updated in the calculation sheet.

7.2 Scheduling through dynamic assignment

The tool, although written mainly in visual basic for applications, is written as such that all maintenance and changes need to be done in excel. Visual basic reads information from excel and translates it into a schedule. During use, the arrays assigned in excel may change and maintenance is required to check if the tool is still working properly every few months. The maintenance would entail mostly too check if all arrays still included all the necessary date.

The dynamic assignment tool was created based on Tecnai systems. For a full implementation of the tool, it has to be adapted for Titan, SEM and SDB systems as well. As Visual basic calls on arrays in excel, the main alterations that need to be made are replacing the order information and skill matrix in the Tecnai tool and updating the arrays to contain the necessary data.

Since the tool is written in excel, the costs of the tool are very low. The only cost the tool will now entail, will be the cost of altering the model for Titan, SEM and SDB systems and maintaining the model. The alterations should not take more than a few days and maintenance may take an hour per month or less. Most of the data for Titan is already analyzed and ready to be implemented in the model, but for SEM and SDB the data needs to be analyzed before the tool can be implemented. This may take somewhat more time, however, the production process is less complicated and production times are shorter. It is therefore expected that this analysis can be easily performed.

FEI will receive a manual for the tool, which will describe how to use the tool in the weekly planning and will help maintain the tool.

8. Conclusion and recommendations

8.1 Conclusion

FEI has little insight into capacity availability. This has caused long waiting times and late deliveries in the past. In order to improve this situation, FEI needed help in deciding the capacity expansion. For this master thesis, three solutions were presented. Using queuing theory, the number of engineers for each team could be determined by a trade-off between number of engineers and waiting times. A model has been suggested to determine a minimal skill matrix, thus, deciding how engineers should be trained. And using dynamic assignment, the best moment for training is determined. Dynamic assignment also determines efficient assignments for each engineer, based on their skills.

For the 46 orders assigned in chapter 6, queuing theory suggested 17 engineers. The model of section 5.2.2 suggested a skill matrix, which was later updated using dynamic assignment. Results showed that the choice of skill matrix, strongly influences the efficiency of the schedules of all models. Current planning benefitted the least from the skill matrix, since the skills of an engineer do not affect the assignment decision. The dynamic assignment tool without future information (k=1) is basically an alteration to the current planning. Instead of letting the first available engineer start an order and if necessary letting a second engineer finish the order, performed considerably less than letting each engineer produce the entire order, especially when the skill matrix was better filled.
Dynamic assignment on the other hand performed even better than the assignment of one engineer to each order, but this difference slimmed when the skill matrix was better filled. The dynamic assignment tool performed better than the current planning for all skill matrices, but for a better filled skill matrix, the results did not differ much from the assignment of one engineer to each order .

Although queuing theory assumes that all engineers are capable of all orders, dynamic assignment agreed with the choice for this number of engineers. Even though, this evaluation was made using production times with less variance, the required workforce estimated by queuing theory was close to the number of engineers required by dynamic assignment. Only the height of the waiting times was strongly affected by the chosen skill matrix.

Stochastic production times strongly affected the dynamic assignment. The results were barely any better than the results for the current planning. If FEI could decrease the variance of the production times (already an objective of FEI), dynamic assignment would perform much better.

The training was well implemented into the dynamic assignment tool. The results show improvements of the number of order that were assigned, and thus started during the year in which the start was planned, the number of orders finishing within the planned quarter and average waiting times. The tool was able to decide on training and made assignment such that the engineers could improve their skills.

The model suggested in this master thesis should help FEI decide on the workforce size and training, both which trainings and when the trainings should take place. Furthermore, the tool should give FEI more insight into the availability of engineers and foresee problems that may occur, as late orders. Due to the variance in production times, the waiting times are decrease by only 10%. However when FEI is able to reduce this variance, benefits may be much higher.

8.2 Recommendations

There are some final recommendations with regard to the analysis and solutions of this report.

- The workforce of Tecnai is already at the required level. The skill matrix can still be improved. The workforce size and skill matrices for the other teams need to be assessed, in order the gain the best results.
- In order to implement the tool for all other production teams, some should be appointed to alter and maintain the tool for all teams.
- Currently, engineers from the SEM group are transferred to Tecnai and from Tecnai to Titan. By implementing queuing theory into the buildplan for all teams, it will become more clear if the team of Tecnai has engineers to spare to transfer to Titan.

Some recommendations for the future:

- It may be interesting for FEI to further asses the production times per step in the future. At this moment too little data was available to determine which distribution the production times follow. If more information was available, it is possible to predict more precise when an order will be finished. This can be beneficial in the timing for material arrivals.
- About three years after an engineer has had a certain training, he needs a training to refresh his memory. This could be included into the model. This way a separate file for training records is no longer needed.
- If the desired skill matrix requires an investment for the training of engineers, FEI may consider releasing their desire to produce a microscope by one engineer as much as possible. A serial production systems allows the same production even if the skill matrix is less filled. It is important to investigate further, before pursuing this option. First of all, FEI should determine if it is desirable to split up their production. Second, serial production causes waiting times between the split up tasks. The resulting waiting times should be compared to the waiting times that can be obtained by dynamic assignment.

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Appendices

Appendix A: Organization Chart of FEI Company II
Appendix B: Order process from order to delivery III
Appendix C: Average time per production step IV
Appendix D: Order configurations and current skill matrices V
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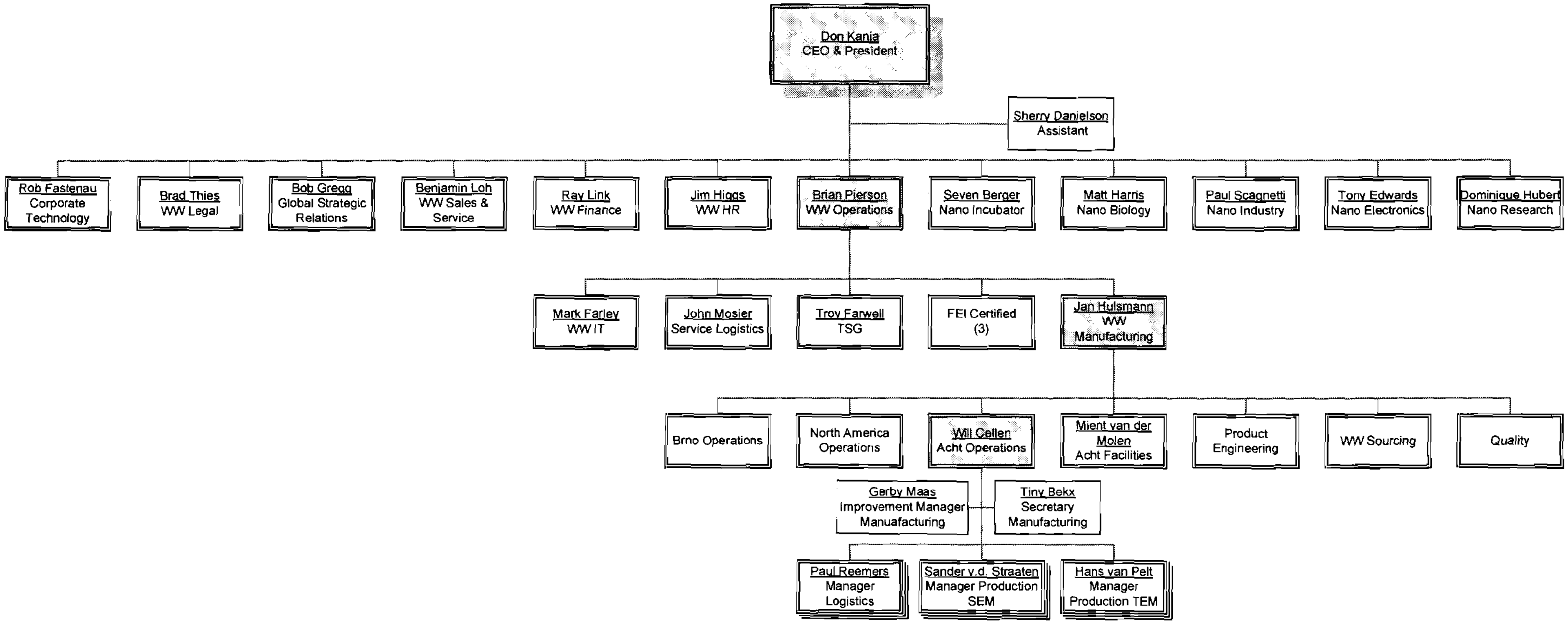
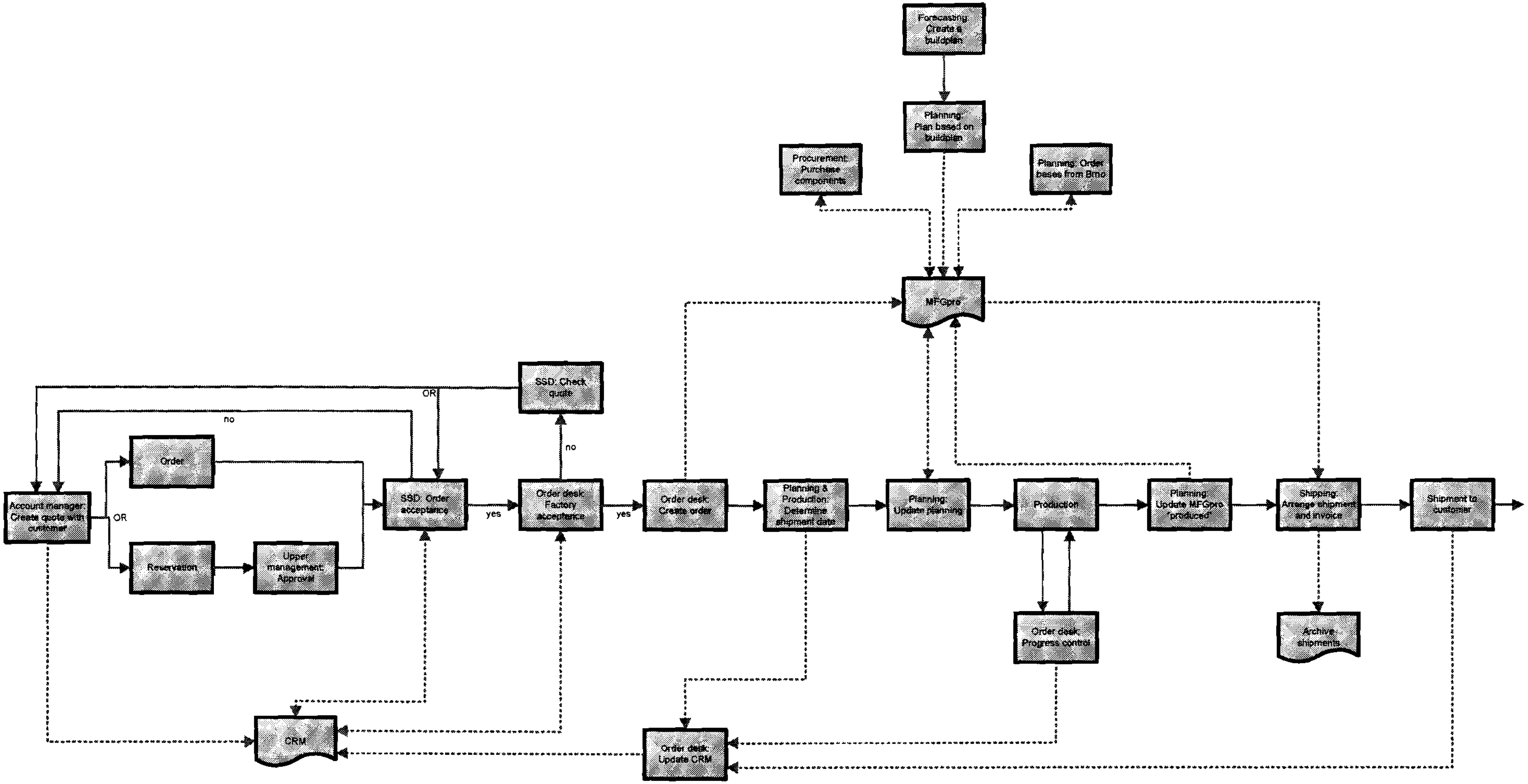
Appendix A: Organization Chart of FEI Company



Appendix B: Order process from order to delivery



Appendix C: Average time per production step

Some production steps are exclusively for Tecnai or Titan systems. The table below shows the production times per step for either Tecnai or Titan or both.

		Production time (days)	
Code	Task	Tecnai	Titan
ma	Montage and plug in	2,4	-
kt	Column test	-	11,1
ot / to	Optics test	9,0	15,6
fc	Montage and conditioning FEG	9,3	-
of	Optics test FEG	12,5	-
hf / th	HOV	9,9	6,1
ac	Accessories	14,5	
ca	Camera	3,0	
gi	Gif	8,8	
ed	Edax	4,1	
st	Stem	5,4	
ic	Image corrector	30,7	
pc	Probe corrector	19,6	
mo	Monochromator	8,8	
ad	Finish and dismantlement	4,8	

Appendix D: Order configurations and current skill matrices

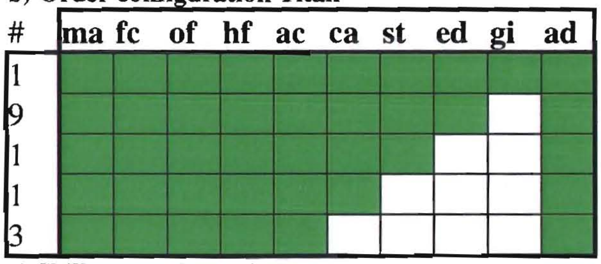
The coloured cells indicate a skill required in the configurations or learned in the skill matrix. The order configurations are listed from most to least common.

#	ma	fc	of	hf	ac	ca	gi	ed	st	ad	Required engineers if BP(2009)=55
22	■	■	■	■	■	■		■	■	■	6,7
10	■	■	■	■	■	■				■	2,6
7	■	■	■	■	■	■	■	■	■	■	2,1
5	■	■	■	■	■	■			■	■	1,4
5	■	■	■	■	■	■	■			■	1,5
2	■	■	■	■	■					■	0,5
2	■	■	■	■	■	■		■		■	0,5
2	■	■	■	■	■		■			■	0,6
2	■	■	■	■	■		■	■	■	■	0,7
1	■	■	■	■	■		■		■	■	0,3
1	■	■	■	■	■		■	■		■	0,3

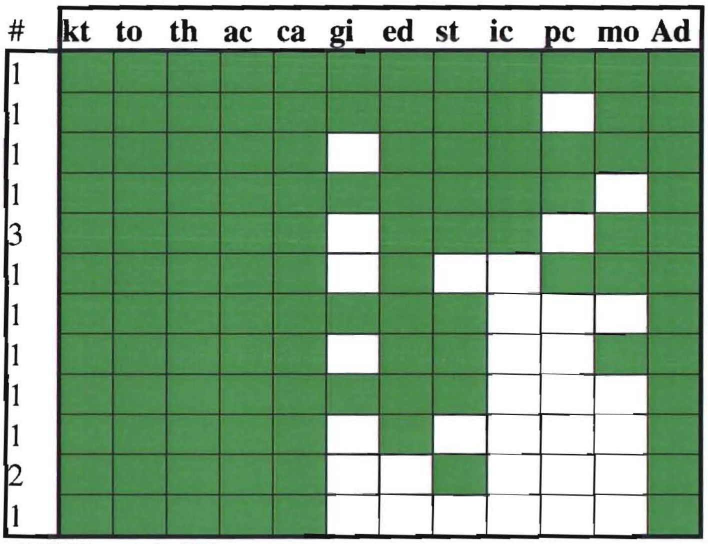
a) Order configuration Tecnai

#	kt	to	th	ac	ca	gi	ed	st	ic	pc	mo	ad	Required engineers if BP(2009)=43
5	■	■	■	■	■	■	■	■	■			■	2,3
4	■	■	■	■	■	■		■				■	1,2
4	■	■	■	■	■	■	■	■		■		■	1,6
3	■	■	■	■								■	0,5
3	■	■	■	■		■	■	■				■	0,9
3	■	■	■	■	■	■	■	■		■	■	■	1,3
2	■	■	■	■	■							■	0,5
2	■	■	■	■	■	■						■	0,5
2	■	■	■	■	■				■			■	0,7
2	■	■	■	■		■			■			■	0,8
2	■	■	■	■	■		■	■				■	0,5
2	■	■	■	■	■	■	■	■				■	0,6
2	■	■	■	■	■		■	■	■			■	0,8
2	■	■	■	■	■	■		■		■		■	0,8
2	■	■	■	■	■	■	■	■	■		■	■	1,0
1	■	■	■	■				■				■	0,3
1	■	■	■	■		■		■		■		■	0,4
1	■	■	■	■			■	■		■		■	0,4
1	■	■	■	■	■	■		■	■			■	0,4
1	■	■	■	■		■	■	■		■		■	0,4
1	■	■	■	■	■	■		■	■		■	■	0,5
1	■	■	■	■	■	■	■	■	■	■		■	0,5
1	■	■	■	■	■	■		■	■	■	■	■	0,6
1	■	■	■	■	■	■	■	■	■	■	■	■	0,6

b) Order configuration Titan



c) Skill matrix Tecnai



d) Skill matrix Titan

Appendix E: Results comparison skill matrices

		CSM	SMM	SM+1	SM+2	SM+3
Order set 1	# orders assigned	37	34	35	38	38
	# orders within quarter	32	28	28	33	33
	average waiting times	3,6	4,3	3,9	3,8	3,5
Order set 2	# orders assigned	34	32	35	34	37
	# orders within quarter	30	28	30	30	34
	average waiting times	2,3	2,5	2,5	2,1	2,2
Order set 3	# orders assigned	33	29	32	34	34
	# orders within quarter	27	24	28	30	30
	average waiting times	3,5	3,2	3,0	2,6	2,5

a) Results current planning

		CSM	SMM	SM+1	SM+2	SM+3
Order set 1	# orders assigned	43	42	43	44	44
	# orders within quarter	37	32	34	41	41
	average waiting times	4,3	4,9	4,2	2,1	2,1
Order set 2	# orders assigned	43	39	40	41	41
	# orders within quarter	37	32	38	40	40
	average waiting times	2,5	2,8	1,5	1,1	1,1
Order set 3	# orders assigned	39	41	42	43	45
	# orders within quarter	31	29	34	38	39
	average waiting times	3,3	4,2	3,3	2,5	2,0

b) Results dynamic assignment k=1

		CSM	SMM	SM+1	SM+2	SM+3
Order set 1	# orders assigned	43	44	44	45	45
	# orders within quarter	41	38	36	40	42
	average waiting times	3,1	4,0	3,8	2,8	2,2
Order set 2	# orders assigned	43	42	41	42	41
	# orders within quarter	38	38	39	40	40
	average waiting times	2,0	1,8	1,7	1,4	1,1
Order set 3	# orders assigned	39	39	43	42	44
	# orders within quarter	32	26	36	37	39
	average waiting times	3,2	4,7	2,7	2,5	1,9

c) Results dynamic assignment k=3