Accomplishing a high delivery satisfaction by switching to a better process-supporting planning system

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Management summary

The Parts Manufacturing department of VDL ETG Almelo, a company which realizes system integrations of mechatronic (sub-) systems/modules, is planning to start with a transition to a new ERP system in the near future. Since it is desired that a new ERP system supports processes such that high performance can be realized, it is useful to have a comprehensive understanding of the processes for composing requirements for such a system.

High performance of quality and logistics are the most important focus points of the Parts Manufacturing department. Important KPIs which are associated with these focus points are high quality performance and delivery reliability. This research has arisen to come up with requirements for supporting processes and achieving a high performance of delivery reliability by implementing a new ERP system and improving logistic processes.

The corresponding research question of the research is:

What are the needs of VDL ETG Almelo in order to improve logistic processes and implement a new digital ERP solution such that the delivery reliability rate of orders substantially increases?

Methods

To come up with requirements for achieving a high performance of delivery reliability, processes at the Parts Manufacturing department of VDL ETG Almelo are analyzed, drawbacks and desires are plotted, and some literature research is done. Subsequently, a model is designed for making decisions during scheduling by linear programming.

For acquiring information about the processes and drawbacks and desires experienced at the department, stakeholders from different sections of the department are interviewed. Thereafter, relations are plotted in flow diagrams to get insight into process relations and root-causes of problems.

During analyzing processes and problems, a need for project planning, project management, dynamic planning and capacity planning has been detected. Therefore, literature research is done in project planning, project management, dynamic planning and capacity planning.

Among others, a project life cycle and dynamic scheduling for dealing with uncertainties are described in literature. The project life cycle is described by 5 phases, which are order acceptance, process planning, scheduling, execution and evaluation & services. According to literature, capacity management is important for managing projects, especially during order acceptance and scheduling. Literature suggests using Rough Cut Capacity Planning for roughly planning capacity during order acceptance, such that decisions can be made about among others due dates, milestones of projects, overtime of work levels, subcontracting and required capacity levels. After project activities are specified, a more detailed planning can be made, which is done during scheduling.

To consider uncertainties during scheduling, literature suggests using dynamic scheduling including a predictive and reactive mechanism. Predictive scheduling is intended to generate an optimal predetermined production schedule, the baseline schedule, which can be used as a guideline for a project. To react on unexpected events and disruptions, reactive scheduling is suggested to modify the baseline schedule.

Results

Based on these findings in literature and decision-making procedures used for scheduling at the department, a model is designed based on the logic of Rough-Cut Capacity Planning and modified to decision making procedures of the department. The designed model is intended to generate a baseline schedule and to make decisions about among others dual source assignment, machine assignment and due dates.

The model considers, among others capacity restrictions, machine loading, dual source restrictions, process durations, precedence relations, and due dates. The model is capable to deal with scheduling problems and capacity planning, which is desired for scheduling orders according to literature. As a result, decisions made by the predictive scheduling model include whether processes are performed intern or outsourced, which machines are assigned to intern processes and what tasks are performed in which weeks. Although these decisions are currently made by manual scheduling, this research demonstrates that scheduling and decision-making can be optimized by automation.

Moreover, a suggestion is made for designing a model for dealing with fluctuating demand, unpredictable events and uncertainties present in the processes by reactive scheduling. It is suggested that modifications, available capacities and decisions made by the predictive scheduling model are used as input for a reactive scheduling model. Furthermore, it is suggested that decisions made by the predictive scheduling model can be considered to gain more insight into, among others, the engineering population.

Recommendations

It is recommended to have a functionality like the designed model for generating a baseline model for making decisions about among others dual source assignment and determining due dates for tasks, which can be used as a guideline for the project. Moreover, it is desired to have insight into consequences of decisions made by the baseline model on engineering capacities, engineering workload, required durations of engineering tasks and the progress of these tasks. Project management and planning are recommended for getting insight into among other deadlines, deliverables, costs, project status monitoring, resource allocation and schedules. Moreover, project management may be beneficial for communication, productivity and resource management.

For controlling processes, an integration between production scheduling and control systems including a scheduling module, a controller and a simulation model is recommended for detailed capacity planning, simulating consequences of modifications and analyzing plan alternatives, which can be used as an input for intern discussions. Moreover, it is recommended to have a functionality for getting clear overviews of the planning, progress of processes, machine loading and capacities.

Besides for controlling processes, overviews are desired for analyzing performances of the department. It is recommended to have overviews of processes, projects including work preparation tasks, products in quarantine and outsourcing and purchasing orders. For products in quarantine, it is recommended to get insight into reasons for quality deviations, consequences of quality deviation, the expected duration of dealing with quality deviation, for how long products are in quarantine, at what production step the problem has occurred, delay and cost of non-quality due to quality deviation and how can be dealt with the quality deviation. Furthermore, it is recommended to have a monitoring functionality for concessions which are requested to get insight into the concession process and when actions have to be succeeded for concessions.

For analysis purposes, it is recommended to have functionalities with analysis options, visual tools and simulation options. It is desired to have a standard dashboard or report for overviews of performances of KPIs. Moreover, it is desired to have functionalities for forecasting orders including an overview with forecasted orders, retrieving data fast and easy accessibility of data. For planning, analysis and controlling purposes, it is desired those orders can be easily selected.

For maintaining, controlling and updating production folders, it is recommended to digitize production folders. Moreover, digitization is beneficial for automation and connect ability with other systems. It is recommended to be equipped for automation for better traceability of orders and for having access to more up to date data. For improving communication and feedback between production steps, sections and systems, connect ability between systems is recommended.

For preventing schedule disruptions, it is recommended to consider uncertainties in project scheduling, to eliminate uncertainties by identifying bottlenecks and to consider safety stock into capacity planning. For dealing with unexpected events and modifications, it is recommended to modify the baseline schedule by reactive scheduling. It is recommended to reschedule orders by giving priority to orders based on urgency.

To conclude, it is recommended to control production processes based on a baseline schedule and to react on unexpected events and modifications by reactive scheduling, to control projects by having insight into engineering tasks, required engineering capacity and available engineering capacity and to control quality by having insight into reasons and consequences of quality issues, products which are in quarantine and clear concession processes. Moreover, it is recommended to include planning and project management functionalities into an ERP system and to include scheduling, controlling and simulation modules.

Recommendations of this research are summarized in the blueprint below:

Recommendations for ERP implementation:

- Project planning & project management functionalities:
  - Resource allocation
  - Schedules
  - Project status monitoring
  - Insight into deadlines, deliverables, progress, engineering capacities and costs
- Scheduling, controlling and simulation functionalities:
  - Insight into progress, machine loading and capacities
  - Feedback options
  - Analysis functionalities
  - Functionalities for capacity planning, dynamic scheduling and/or stochastic scheduling
  - Simulation functionalities
- Functionalities for controlling quality issues:
  - Insight into quality issues, reasons & consequences of quality issues, costs of non-quality, expected delay and expected duration of dealing with quality issues
  - Functionality for putting products into quarantine
  - Functionality for controlling products in quarantine and for controlling products in a concession process
- ERP system which includes connect ability with other

Recommendations for process improvement:

- Controlling logistic processes
- Controlling quality
- Considering uncertainties
- Identifying bottlenecks
- Update intermediate progress
- Rescheduling to react on unexpected events and modifications
- Capacity planning, dynamic scheduling and/or stochastic scheduling
- Simulating consequences of decisions
- Digitizing production folders

Roadmap for further research:

- Investigating impacts of migrating to another ERP system
- Investigating critical success factors for ERP implementation
- Investigating misfits, risks and barriers of ERP implementation
- Simulating expected effect of migrating to another ERP system on performance of KPIs

Figure 1. Blue print with recommendations

Contents

1. Introduction

1.1. Company Context

This master thesis is performed for the Parts Manufacturing department of VDL ETG Almelo. VDL ETG Almelo is a company which realizes system integrations of mechatronic (sub-)systems/modules of its customers. As a supplier, VDL ETG Almelo covers the whole chain from (co-)design to parts manufacturing, assembling and quality-control.

VDL ETG Almelo is one of the production units of the VDL Enabling Technology Group (VDL ETG). Besides in Almelo, VDL ETG has production units in Eindhoven, Singapore, Suzhou and Trübbach. VDL ETG is a tier-one contract manufacturing partner with global operations. This means that VDL ETG supplies systems and modules directly to Original Equipment Manufacturing (OEM) companies. The customers of VDL ETG are OEM companies that have a leading role in high-tech manufacturing equipment and users of advanced production lines. VDL ETG aims to exceed the customers' expectations on the basis of high quality and service level in the supply of mechatronic modules.

VDL ETG has a broad experience in engineering, prototyping and serial manufacturing of products/systems for the semiconductor industry, analytical instruments, solar systems, medical systems, aerospace and mechanization projects. Manufacturing at VDL ETG is characterized by high complexity and relatively small production numbers. Moreover, VDL ETG provides customer-specific production mechanization as well, which is the focus of VDL ETG Projects.

1.1.1. History of VDL ETG

VDL ETG is part of VDL since 2006. In 2006 the Enabling Technology Group is bought by the VDL Groep, since the VDL Groep strives to controlled growth and the maintainability of work. Before, the company was part of Philips, which was founded in 1900 as "Philips Machinefabrieken" and was renamed in 2000 into "Philips Enabling Technologies Group". Before the company became part of the VDL Groep, it was already developed into a worldwide supplier of high-quality mechanical components, modules and systems. As part of the VDL Groep, the company is even better able to adopt a leading position.

1.1.2. VDL Groep

VDL Groep is a family company, which is developed into an international, industrial company that focusses on innovation, production, assembling and selling subassemblies, busses and other finished products. VDL Groep contains 89 operating companies which are located in 18 countries. In total more than 13000 employees are working at VDL Groep. All these operating companies are flexible and independent companies with their own specialism. The power of VDL Groep is the cooperation between the companies. Since VDL Groep contains many diverse companies with their own specialties, the products of VDL Groep are very diverse as well, products of VDL Groep are among others busses, doppers and automotive machines.

As mentioned before, the specialism of VDL ETG Almelo is the system integration of mechatronic (sub-)systems/modules.

1.1.3. VDL ETG Almelo

VDL ETG Almelo is continuously growing. In 2017 renovation and extension of the building is done and due to continuous growth of staff the building does not suffice anymore. Currently, building a new production hall has started.

Inside the company, the business is driven on working with dual source, which means that the company makes use of both producing and purchasing orders. Around 10-20% is produced inhouse and the rest is purchased. In practice only complicated production is done inhouse, such that quality can be guaranteed. By using dual source, a decision can be made for orders if the order will be produced or purchased, as long as the deadline is met.

Especially at the Parts Manufacturing department it is very important to meet deadlines, since supplying late will have significant consequences on the planning of the Assembly department. Therefore, planning is done such that deadlines of supply is met. Supply can be met by either production or purchasing. If during production a lack of capacity arises, then adaption of production steps may be outsourced.

1.1.4. Parts Manufacturing department

Parts produced at the Parts Manufacturing department contain two types of parts, namely mechanical and sheet parts. The total number of orders which are ongoing at the Parts Manufacturing department are around 1200 to 1500 orders, from which more than 95% are supplied intern to the Assembly department. The remaining 5 % are supplied to direct customers.

1.2. Process Context

At the Parts Manufacturing department of VDL ETG Almelo a wide range of parts are produced which are in different phases in the Product Generation Process (pgp) process. Products produced at the Parts Manufacturing department of VDL ETG are produced after arrival of customer orders or if customer orders are expected based on forecasts. A customer order includes the demand of a specific product, a demanded delivery date and specifications which have to be met. During the work preparation trajectory and during production, customers may demand for some adjustments for projects. Most orders, around 80% of all orders, are in the volume production phase and are called flow products. Other orders, may range between the initialization phase to the pilot phase, from which most orders are situated later on in the pgp process. The pgp process is shown in figure 2.

Figure 2. Product generation process

In figure 2, the pgp process is shown. Phases initialization, concept, design and proto are orange colored in figure 2. New projects are situated in these phases. Dependent on the request of the customer, a new project starts from one of these phases. For example, if the request is “build to spec”, the project starts after specifications are specified in the initialization phase and if the request is “build to print”, the project starts after a design is made. Estimating the expected duration of the work preparation of orders in the earlier phases are most complex, especially in the concept and design phase, since these durations may contain much variation.

The pilot phase, the phase in which production is stable, but not ready for volume production, is yellow colored in figure 2. Orders which are situated at this phase can be considered as projects, since still some work preparation and improvement is required. Nonetheless, parts of these orders are not new anymore. Therefore, planning of the work preparation trajectory of these orders is partly done by logistics. For orders in the proto and pilot phases, Factory Engineering is responsible for controlling the quality of production.

When the status of an order is ready for volume production, the responsibility of controlling quality of the production process is handed over to production and Quality Engineering, which assist production with quality control. Orders which are ready for volume production are situated in the volume production phase, which is green colored in figure 2. Parts which are situated in the volume production phase are flow products. Production of these parts can start fast, since work preparation tasks are not required anymore or only minor modifications need to be done.

In general, most parts are situated in later phases, which means that more parts are situated in the proto phase than in the concept and design phase, even more parts are situated in the pilot phase and most parts are situated in the volume production phase.

The production of parts can thus be divided into projects and flow products. The production of an product in small series can be classified as a project as long as it is not ready for volume production and otherwise as a flow product. Projects containing parts to be produced can be divided into new and existing projects. Existing projects are produced earlier, but are not ready for volume production yet, these projects are usually situated in the pilot phase. During earlier production of these projects, experience is gained with the product and its production, which has induced adjustments and improvements for this project. Therefore, for existing projects, adjustments and improvements have to be made during work preparation prior to production. Usually, required actions, for adjustments and improvements, of existing projects are well-defined, easy to plan and less time-consuming than the work preparation tasks of new projects.

The main differences in the complexity of planning orders between projects and flow products are that the demand of flow products can be put more realistic over time than of projects and anticipating on time is more feasible for flow products than for projects. Moreover, for projects it is more difficult to guarantee quality, since time pressure is at the cost of quality and projects have to deal with a learning curve, because in the beginning estimations are used before real data is available.

Projects are more difficult to arrange, since they are known relatively late and high quality is still required. Before production of projects can start work preparation tasks have to be performed, while for flow products usually only minor modifications are required. For flow products around 95% of preparation tasks are fixed, the only modifications which have to be done by Factory Engineering and programming are related with maintenance and other minor process modifications. Therefore, the work preparation of projects is significant longer. Besides some minor modifications, for flow products some actions need to be performed by Quality Engineering in case of deviation and disapproval. Because of the longer preparation phase for projects and the importance of fast delivery, Factory Engineering, Programming and Purchasing should start immediately when a project is obtained.

1.3. Research motivation

The planning system currently used by the parts manufacturing department of VDL ETG Almelo is BaanIV, which is an ERP system from ’78. Since, BaanIV will not be supported anymore in the near future, it is needed that the Parts Manufacturing department of VDL ETG Almelo will transfer to another planning system. Moreover, the situation in which BaanIV is designed in ’78 is not in line with nowadays demand anymore. Over years external tools are built for having more extensive functions, forecast options and better overviews. These external tools have to be maintained separately. For simplicity and better overviews it is desired to introduce the functionalities of external tools in a new ERP system.

Modern ERP packages, which are designed for modern businesses, have more and more extensive functionalities and are furnished for automation and digitalization. While planning is inserted by hand in the current ERP system, newer systems are able to insert the planning automatically.

Nowadays, a need for automation occurs even more at VDL ETG Almelo, because of growth and expansion. With the number of ongoing orders the company has nowadays, it is even not feasible anymore to plan by hand.

Therefore, the Parts Manufacturing department of VDL ETG is planning to start with a transition to a new ERP system in the near future. Since the Parts Manufacturing department of VDL ETG Almelo is changing from planning system, it is useful to have a comprehensive understanding of the processes and the way the current ERP system and external tools are currently being used. It is desired to have a planning system which assist in planning the production such that an ideal mix of parts are produced which utilizes full capacity with maximum return and a high delivery reliability is reached. Therefore, a statement of requirements for a new ERP system is required.

In 2020, a project for the transition to a new ERP system has started by requesting investment from the headquarter of VDL ETG, which is located in Eindhoven. Other actions which are already done by another company of the ETG group to find out what criteria are required for a new ERP system are among others, having a look into some ERP packages with scheduling functions, organizing SAP workshops for employees from multiple departments and using Vendor-Managed-Inventory (VMI) to figure out what is required from suppliers. After these actions, a selection of 3 potential ERP packages are made, which are InforLN, SAP and VBS. From these 3 potential packages, the investment proposal of InforLN is accepted by the headquarter.

To get insight in what modules of InforLN are needed, both theoretical and practical proofs are needed. To come up with theoretical and practical proofs for required functionalities, this assignment arises.

Besides doing research into requirements for a new ERP system, investigating the processes for improving logistics is desired. Furthermore, the manner in which employees are informed by the system about tasks, materials, orders and if a splitlist or trigger are received when a task should be done are interesting to know to gather a better understanding of information flows. Moreover, it is desired to investigate how projects can be managed and in what manner digitalizing can be beneficial for improving and supporting processes.

Since, the Parts Manufacturing department of VDL ETG Almelo is planning to be ready for a transition near upon to invest in a new planning system and making the processes ready for digitalization, the research is urgent.

1.4. Problem description

The core problem of this research is that the delivery reliability is quite low, while VDL ETG aims to a high service level. The delivery reliability is low, since delivery meets the due date for only 65 - 75% of the orders. The delivery is regularly late, because the planning tool calculates with infinite capacity and the engineering tasks are not visible, which results in an infeasible planning. Moreover, the company is growing and the number of projects is growing as well, while managing projects is complex. To manage projects better, some project management is required. However, the company lacks some project management. Furthermore, currently the company is not organized to deal with uncertainties, while much uncertainties are included into the processes. Moreover, planning is time-consuming in the current situation and quality problems are not visible.

1.5. Research objective

1.5.1. Goal

The goal of this research is to investigate how processes at the Parts Manufacturing department of VDL ETG are organized, how the current ERP system and external tools are being used and to plot what VDL ETG Almelo needs to improve the delivery reliability and how these needs can be fulfilled.

While increasing the reliability rate for delivery is the main goal of this research, the goal of the production planning should be taken into account. The goal of the production planning is to produce an ideal mix of parts such that as many machine hours are utilized with maximum return. Therefore, a tradeoff should be made between maximum utilization of machine capacity against maximum return.

Moreover, it is desired to plot what is needed for different types of processes, orders and uncertainties into the processes.

1.5.2. Scope

The assignment focuses on the interface of ERP implementation, process improvement and planning & scheduling. Not only operational planning is taken into account, but planning of FE, Quality Engineering and programming are taken into account as well.

The research only refers to the Parts Manufacturing department which produces both mechanical as sheet parts. Other departments of the company are only considered for the interrelations, input and output of the Parts Manufacturing department.

Since the Parts Manufacturing department has to deal with both projects and flow products orders, it is useful to focus a bit more on project planning such that project orders can be planned better. Moreover, it is desired to take some uncertainties into account and to find out how to deal with uncertainties.

The scope of this research is the end of the pgp process, the yellow and green phases of figure 2, which are the pilot and the volume production phases.

This assignment is the start phase of the transition process. In this phase, the problems and bottlenecks of the current ERP system and processes are analyzed and desires/needs are drawn. Based on the needs, a theoretical foundation with planning methodologies which supports the needs will be described. With the theoretical foundation and the needs as a basis, some research is done to find out what functions are present in available ERP modules and how needs could be fulfilled by a linear program.

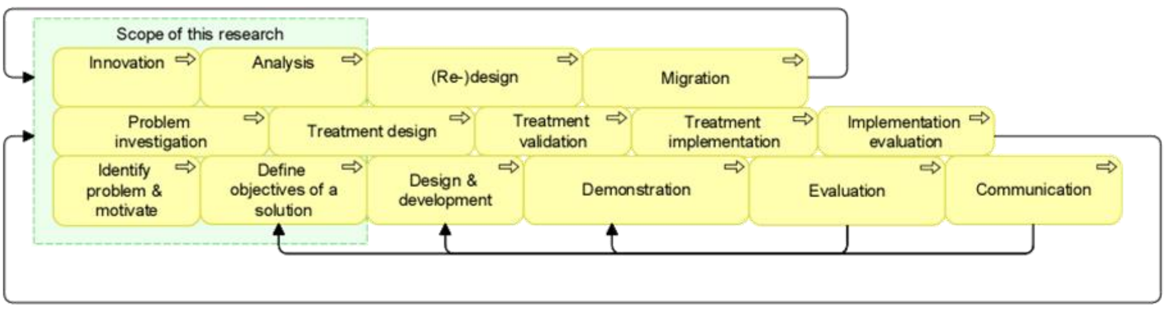

Figure 3. Scope of the research

After (Berg, van den et al., 2008; Peffers et al., 2007; Wieringa, 2014).

1.5.3. Deliverable

The deliverable is a blue print with an overview of needs for the new ERP system, needs for modifications of the processes and critical elements which should be considered during the implementation phase. Moreover, the deliverable includes a model which may be beneficial for improving logistic processes and planning.

1.6. Research questions

The main research question is:

What are the needs of VDL ETG Almelo in order to improve logistic processes and implement a new digital ERP solution such that the delivery reliability rate of orders substantially increases?

To solve the main question, the research is divided into the following 3 stages:

- **The current situation**
- **The problems, shortcomings and bottlenecks in the current situation**
- **Implementations needed to fulfill needs**

1.6.1. The current situation

In the current situation stage, questions with regard to the KPIs of the department, the current processes and the current planning system are asked. Questions which are answered in the current situation stage are as follows:

1. How are processes currently organized?
    a. How is the preparation trajectory currently organized?
        i. What are tasks which have to be done in the preparation trajectory?
    b. How is quality control currently organized?
    c. How is logistics currently organized?
    d. How are production processes currently organized?
    e. How are product generation processes currently organized?
    f. How are the dual source processes currently organized?
2. Which stakeholders are involved in the chain of the Parts Manufacturing department?
3. What are the current KPIs of the Parts Manufacturing department?
4. What are the basic functionalities of current ERP system?
    a. What planning methodologies are included into the current ERP system?
    b. What other systems are used in the current situation and are these systems connected to the current ERP system?

1.6.2. Shortcomings, bottlenecks and problems

After we clarified the current situation, questions with regard to shortcomings, bottlenecks and problems in the current situation are asked. Therefore, questions which are answered in the second stage are as follows:

1. What are ERP system related shortcomings experienced by stakeholders?
2. What are process related drawbacks experienced by stakeholders?
3. To what extent are shortcomings related to logistics experienced?
4. To what extent are project related shortcomings experienced?
5. To what extent are quality related shortcomings experienced?
6. Why is the delivery of orders regularly not met on time?

1.6.3. Implementations needed

In the last stage, questions with regard to needs and implementations of the new planning system are asked. Therefore, the following questions are asked in the last stage:

1. What are the desires of the stakeholders when considering a new ERP system?
    a. What are logistics related desires of the stakeholders?
    b. What are project related desires of the stakeholders?
    c. What are quality related desires of the stakeholders?
    d. What are digitalizing related desires of the stakeholders?
    e. What are analysis related desires of the stakeholders?
2. What are the needs for improving the delivery reliability?
    a. What are the needs to cover the root causes of late delivery?
3. How can these needs and desires be fulfilled?
    a. What planning methodologies are covered in literature for related processes and needs?
    b. To what extent can these needs be modeled by a linear program?
4. What are important factors to take into consideration during the implementation phase?

1.7. Research approach

To get more insight into the causes of late delivery and how the delivery reliability can be improved, the problem is approached by analyzing the current situation, performing a problem analysis and investigating what are the needs and how these needs can be fulfilled. The research approach is structured by these elements to answer the research questions.

First of all the current situation is analyzed. This analysis consists of a description of how the department is organized, a process analysis, a description of the uncertainties included into the processes and a description of the current ERP system. The description of how the business is organized includes the KPIs of the department, some background information of the stakeholders included into this research and a description of how the preparation trajectory, production, quality and logistics are organized. The process analysis includes an analysis of the product generation process, an analysis of the processes of different types of products, a description of the process chain, the complexity and the diversity of processes, an analysis of the dual source process and the process of price information. The description of the uncertainties includes forecasts of orders and the uncertainty of machine failure. Last, the description of the current ERP system includes a description of the system, systems which are connected to the ERP system and other systems related to the processes.

After the current situation is analyzed, a problem analysis is done, which intend to make clear what the problems are and what problems are process related and what problems are ERP system related. Moreover, project related shortcomings, logistics related shortcomings and quality related shortcomings are outlined in the problem analysis. Furthermore, an analysis into the reasons for late delivery is done in the problem analysis.

After the problem analysis, an investigation of requirements is done. This investigation includes desires of stakeholders and needs from insights into the current shortcomings. The investigation of needs and desires includes logistic related desires, project related desires and desires with respect to controlling quality. Moreover, the investigation of needs and desires elaborate needs of analysis options and needs of automation, digitalization and connect-ability.

After the investigation of needs and desires, some literature research is done and a solution design is given how (a part of the) needs can be fulfilled. Last but not least, an overview of important factors described in literature which should be taken into account in the implementation phase is given.

For describing the current situation, analyzing shortcomings and problems in the current situation and investigating the needs and desires, stakeholders are interviewed and flow diagrams are made to analyze processes, (inter)relationships and root-causes.

Based on the processes, problems, shortcomings, desires and needs, some literature research is done. Based on this literature research, interesting planning methodologies are used to model a linear program in AIMMS which is in line with the processes and needs for the Parts Manufacturing department of VDL ETG Almelo. Besides literature research related to the needs and processes of the company, literature research is done for investigating important factors to take into account in an implementation phase to a new ERP system.

1.7.1. Outline of the report

The remainder of the report is organized as follows. In chapter 2 the current situation is described with a description of how the department is organized, a process analysis, a description of uncertainties included into the processes and a description of the current ERP system. We intend to clarify the shortcomings, bottlenecks and problems in chapter 3. In this chapter, the problems experienced by the stakeholders are described and a root-cause analysis to come up with the reasons for late delivery is done. Moreover, this chapter intends to make clear what process related problems/drawbacks and what ERP system related problems/drawbacks are. Furthermore, logistics related shortcomings, project related shortcomings and quality related shortcomings are outlined. Based on the findings of chapter 3 and the desires of stakeholders, needs and desires are investigated in chapter 4. This investigation includes logistics related desires, project related desires, quality related desires, needs for analysis options and needs for automation, digitization and connect ability of systems. In chapter 5, a literature review is done to find planning methodologies which are in line with the processes and needs of the Parts Manufacturing department of VDL ETG Almelo. In chapter 6, a solution design is designed, and build based on planning methodologies found in literature, the processes and needs of the department and based on linear programming. In the end, conclusions and recommendations are drawn in chapter 7.

Chapter 2. Context analysis

In this chapter a description is given of the department, processes of the department, uncertainties in the processes and a description of the current ERP system.

2.1. The department

The Parts Manufacturing department is responsible for two types of parts, namely mechanical and sheet parts. Nowadays, around 1300 orders, containing one or more orders of the same product, are running simultaneously.

Customer orders placed are always accepted, independent on available capacity and required technology. For every order an investigation is done if the order will be (partly) produced intern or purchased. If an order will be (partly) produced intern, a planning investigation is done if all process steps are performed intern or if some process steps will be outsourced. During planning investigation capacity constraints are taken into account, since production capacity is fixed. If more capacity is required than available intern, help of suppliers/subcontractors is needed.

Since, the department is dependent on the available capacity, the planning is capacity-based. Moreover, customer orders are received continuously. Therefore, the business of the department is driven on continuous, capacity-based planning, in which the goal is to produce with utilizing maximum capacity with maximum return and maximum delivery reliability.

The business of VDL ETG Almelo is rather fused with Baan IV, which is the current ERP system. Both the current ERP system and the way of working at the company are relatively outdated. The labor division is organized such that the responsibility at the workfloor is low, since logistics controls the status of the processes and arranges that materials are available on time. Currently, logistics gives oral updates and papers with lists of important orders to production. Much paper work is used in the factory and the company is lagging behind digitization. A significant part of the paper work could be digitalized. Among others, a migration to a new ERP system can help to become a more digital company.

2.1.1. The stakeholders

The migration to another ERP system may have consequences for employees of the company. Therefore, employees are important to take into consideration during the transition to a new ERP system. For that reason, it is important to investigate who the stakeholders are, what the stakeholders do and what they need from an ERP system and/or other tools.

Inside the Parts Manufacturing department multiple stakeholders are involved. These stakeholders are from different divisions, which have their own tasks and have a different view on the ERP system and the processes of the department. In this section some background information about the stakeholders and the tasks of the stakeholders is given.

The stakeholders considered in this research are the managers of the Parts Manufacturing department and the Supply Chain department, the manager Digitization and the heads of the divisions Planning & Logistics, Factory Engineering, Programming, Quality Engineering, Quality Control, Production and Purchasing.

Manager Parts Manufacturing department: The manager Parts Manufacturing is responsible for the department and coordinates the department. The Parts Manufacturing department produces both mechanical and sheet parts. Planning and organizing the manufacturing of mechanical and sheet parts are done independent of each other. Controlling the processes starts with a holistic view, which consist of a rough overview of the whole process, which is zoomed in later on to have a more refined insight into details.

Mechanical manager of the Parts Manufacturing department: The mechanical parts production is bigger than the sheet parts production. Therefore, besides a manager for both the mechanical and the sheet parts, the department has a mechanical manager as well. The mechanical manager arranges and coordinates the performance of the overall process of the mechanical parts production. The mechanical manager heads the following sections: logistics & planning, Quality Control, Factory Engineering, programming and production.

Manager Supply Chain department: The supply chain department is a supporting department, which manage the planning of the ERP system and fills customer orders and forecast demand in the ERP system. After the Supply Chain department filled in the demand information into the ERP system, this information becomes available for the Parts Manufacturing department.

Manager Digitization: Manager Digitization is a quite new position at VDL ETG, which can be seen as a side position. The manager Digitization is working for the whole ETG group in the Netherlands, which means that he is working for multiple ETG companies. The main task of the manager Digitization is arranging digitization of processes. Currently much paper work is used in the company. It is intended to have a transition into digital information. Until now, automation projects are done in Excel. In the past automation projects were done by Factory Engineers, however, it was desired that a more company-broad view was taken into account during automation of projects. Therefore, this side position is created.

Since Infor is stopping with the support of Baan IV near upon and for becoming a digital factory a transition to a modern ERP system is required, the Manager Digitization is working on the transfer of a new ERP system. Important criteria for the selection of a new ERP system are customization, risks and the implementation trajectory.

Head Logistics & Planning: The head logistics & planning is responsible for production planning and machine loading from A till Z including purchasing of materials. The team includes both operational and tactical purchasers. The customers of the Parts Manufacturing department are for approximately 90 - 95 % intern customers and for 5 – 10 % extern customers. The logistics & planning section is responsible for a high delivery reliability and optimal machine loading at every moment. Therefore, the logistics & planning section have to balance a high delivery reliability with high machine loading.

Besides order-dependent tasks, logistics works on improvement projects. These improvement projects consider mainly optimizing and automation of ERP devices. The company uses the plan-to-win strategy and focuses on capacity. Operational planners focuses most on planning with current capacity. While tactical planners look half a year to a year forward to forecast what will happen and what will change. For the forecasted orders, it is analyzed what operations have to be done and if production is equipped to perform these operations.

Head Factory Engineering: The head Factory Engineering is the manager of the Factory Engineers. Factory Engineers are a kind of project leaders focused on production in the factory itself. Factory Engineers arrange the manufacturing processes and prepare work proceedings for the manufacturing processes. Work proceedings are prepared in Siemens NX. Subsequently, the documentation is saved in Siemens Teamcenter. Customers are cost competitive and demand for a short development leadtime. Factory Engineers accompany customers in designing products and arrange the manufacturing process. Meanwhile, Quality Control request for quality requirements. Moreover, the planning of the manufacturing process has to be aligned with Planning & Logistics. Furthermore, Factory Engineering analyzes sometimes materials ordered for parts, which orders are not released yet, to check the time between arrival and release.

In general, Factory Engineering is working continuously with backlogs, such that actions are picked up directly. According the head Factory Engineering, durations are not controlled at Factory Engineering since everything which has a different duration as estimated has a reason.

Head Programming: Programming programs files for the production process. Folders for programming are prepared by Factory Engineering. The files are cut in multiple blocks, such that milestones can be controlled. Programming for preparation tasks, operations and verification are done in separate blocks.

Besides programming for new projects, programming works on maintenance of machines and improvements of processes as well. If a problem occurs, programming intends to fix the problem. Moreover, programming keeps their own processes up to date. Furthermore, programming initiates tests to record production knowledge and acquire knowledge about the control of new machines.

Head Quality Engineering: Quality Engineering handles complaints. Complaints are coming from both intern and extern, since processes are done both at the company itself and at multiple outsourcers. In case of intern complaints, the failure is reported in CAQ REM by Quality Control. Products which are red colored in CAQ REM are in quarantine, which means that products consist deviation.

Head Quality Control: At this moment, Quality Control consist of 1 section and 2 sections will be added soon. 3 measuring machines are at Quality Control to measure the parts. If a product is accepted, the process will be continued, while if a product contains a deviation, the part is going in quarantine. Moreover, Quality Control checks parts which are going to an outsourcer before it is send to the outsourcer. This action is called MeCo. Main tasks of Quality Control are reporting operations as finished and putting products in quarantine.

In general, Quality Control just checks important sizes. However, for new projects, the measuring program has to be programmed by Quality Control. Other tasks for Quality Control are calibration and checking measuring materials.

Head Production: Production, which is also called the workfloor, is the section which manufactures the products. For production, controlling hours for having insight into costs is most important. Therefore, one of the tasks of the head production is account for hours. This can be done by requesting data about hours in the ERP system and correct that data if necessary. Moreover, reporting operations as complete if it is not done yet by the operator is a task for the head production. The function of head production in the ERP system is coach. According the head production, the interface in the ERP system is quite limited.

Head Purchasing: For Purchasing VDL ETG in Almelo has one Purchase manager. Furthermore, all Purchasers are divided over departments. The heads Purchasing at the Parts Manufacturing department (also called Mechanics, since it is actual the own machine factory of the department) are Strategic Purchasers. The Parts Manufacturing department is the supplier of the assembly department. In total 6 Purchasers, from which 2 strategic purchasers, 3 operational purchasers and one supportive purchaser, are working at the Parts Manufacturing department.

The heads Purchasing, Strategic Purchasers, are responsible for arranging outsourcers for purchasing products if the production in the factory itself is overloaded. Furthermore, the heads Purchasing determine the policy of the department. The heads Purchasing are responsible for preparing a purchasing plan, set the purchasing plan and improve it. Furthermore, the heads Purchasing select suppliers and are in this way support of the operational purchasers. Purchasing is done for both materials and orders. Project (Strategic) purchasers do the purchasing of orders, while operational purchasers purchase materials. In this manner, purchasing is a bit supply chain furnishing. Moreover, Strategic Purchasers are helping the other purchasers if somewhere help is needed.

The Strategic Purchasers of Parts Manufacturing are responsible for setting up, rolling out and implementing the Purchase plan/policy for the department. The operational purchasers are responsible for placing orders and having contact with the suppliers about costs and technical aspects. The supportive purchaser is responsible for controlling order confirmations and the pursuit of orders which are not on time. The Strategic Purchasers collaborate closely with the Planning & Logistics section. Tactical and Operational purchasers are even covered by the Planning & Logistics section.

In case of projects, tasks of Strategic and Operational purchasers have overlap. Controlling orders of new projects is one of the tasks of the Strategic Purchasers, while controlling orders is a task of Operational Purchasers. In the proto and pilot phases of a project, the order flow is controlled by Strategic Purchasers. When the production process runs, controlling the order flow is taken over by operational purchasers.

Activities which have to be done in the ERP system by the Strategic Purchasers are adding materials of new projects into the ERP system and extract data from the ERP system for analyses.

The interface of Strategic Purchasers in the ERP system contain functions for creating and managing purchasing orders, product management (Purchase Procurement), maintaining supplier data, doing adjustments and managing contracts.

2.1.2. KPIs of the department

Together, the stakeholders strive to high performance of the department. To control the performance of the department, every week on Monday a Performance Indicator weekly flow meeting is organized for managers and the heads of the different sections. In this meeting, KPIs (Key Performance Indicators) are reviewed and discussed. Once in the two weeks, the discussion about the performance indicators is going more in detail. Information about among others efficiency, delivery reliability, machine loading, backlogs, downtime orders, unmanned hours, orders with deviation, actual planning, stock and anonymous result are reviewed and discussed.

The performance of the department is determined by multiple indicators, from which the focus points of the company are QLTCR. QLTCR stands for quality, logistics, technics, costs and risks. The corresponding indicators of these focus points are quality, delivery reliability, process performance, costs and risks. The most important indicators at the company are the focus points quality and logistics. KPIs at the Parts Manufacturing department are most related to operational level. For some products it is easier to comply the requirements than for other products.

One of the most important KPIs is the delivery reliability, which is dependent on the performance of both sales, assembly and supply, which is applicable for both intern manufacturing and outsourcing/purchasing. Both an overall delivery reliability and a delivery reliability per supplier is determined, since the reliability of assembly is dependent on the delivery reliability of a supplier. If the delivery reliability of the Parts Manufacturing department is low, the planning of the assembly department may not be reliable. Indicators related to delivery reliability are among others machine loading and Confirmed Line Product Performance (CLIP). The CLIP indicates in what extent agreements are kept. Moreover, the actual planning is reviewed to check if the actual planning includes bottlenecks.

Besides the delivery reliability, for outsourcers quality performance is an important KPI, for purchasing the reject rate is an important KPI and for Logistics & Planning machine loading is an important KPI. In general, the delivery reliability decreases when the machine loading increases. The other way around, this applies as well. Therefore, the main challenge is to find the optimum balance between delivery reliability and machine loading. The complexity of delivering on time is dependent on among others the complexity of production, the stability of production and the length of the whole process chain.

Moreover, the performance of occupied hours is an important KPI, for which Logistics & Planning and Production are responsible together. The performance of occupied hours is determined by an overview of exceeded hours, worked hours of the department and per operation, the number of hours clocked, the number of hours reported as finished, the number of indirect hours of operators and the efficiency of manufacturing, which is calculated by the ratio of precalculated and recalculated durations of tasks. For Production, the clocksystem is leading in determining performances. The performance is calculated per production cell, such that every production cell has its own responsibility. For calculating the efficiency of the production cells, the precalculations are based on forecasts, validations and adjustments from simulations and recalculations of protos.

Besides for Production, efficiency is an important KPI for programming and Quality Control. Other KPIs of Quality Control are lead time, delivery reliability and backlog. In the current situation, products which are in quarantine are in the ERP system still at the control list of Quality Control. Consequently, lead times and backlogs of parts in quarantine are not representable for the actual performance of Quality Control.

The number of backlogs, downtime orders and orders with deviation are controlled to maintain delivery reliability and to prevent lateness. For reviewing backlogs, information of operation hours which are planned in backlog and operation hours planned in the coming weeks are taken into consideration. By doing this, it can be analyzed if backlogs may cause problems.

Besides logistics, quality is the other focus point of the company. To control quality, complaints are always discussed and it is determined what complaints are relevant. The main KPI of Quality Engineering is minimizing/eliminating customer complaints. The performance of this KPI is calculated by the number of complaints from assembly and customers over the total number of supplied parts, which may not be higher than 0.05%, which is not met in the current situation. Other KPIs reported are cost of non-quality, outstanding actions and rejects of both intern and suppliers. Cost of non-quality signify that in case of quality issues, Quality Engineering has to put effort, work and time in that order, which costs money.

The anonymous result is an important indicator to control overall costs. Expected costs for projects are based on forecasts. These expected costs are transferred to running projects. The resulted costs of projects are taken anonymous, such that in case of deviation, a project will not increase significant in costs, but the additional costs are divided over multiple projects. The anonymous result should be around 0, such that actual and expected costs cancel each other out.

Moreover, stock levels are reviewed to control that stock barriers are not exceeded. For production efficiency, it may be beneficial to produce in more optimal batch sizes, while for financial and storage area perspectives it is beneficial to minimize stock levels. Especially for parts/systems which are rarely sold, stock is undesired.

2.1.3. Objectives based on regularity of selling a system/part

The regularity of systems and parts sold variates from rarely to regular. For example if a system or part is only sold once a year, it is rarely sold and having stock is not an option. While, if a system is sold multiple times a week or month, having stock is not a problem. In that situation, it is desired to focus on efficiency by producing more optimal batch sizes. The range of variation of the selling regularity of systems/parts is shown in figure 4.

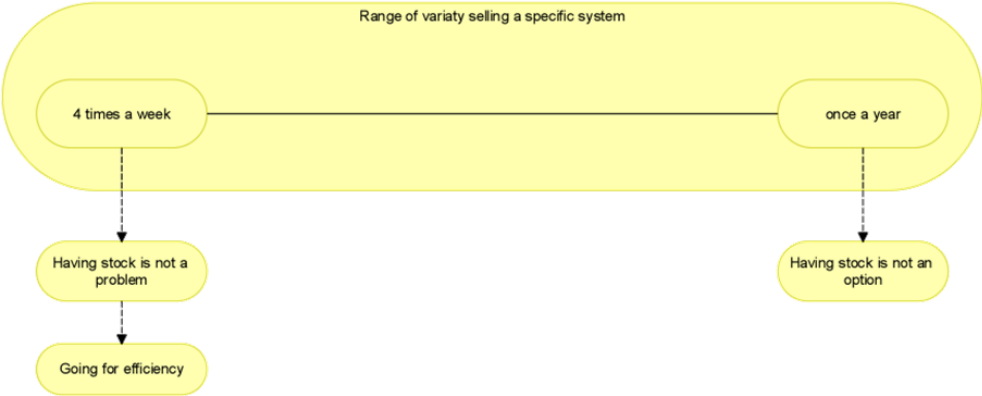

Figure 4. Regularity of selling a specific system

Especially for parts which are produced intern, it is beneficial to produce in optimal batch sizes if that part is sold sufficient regular. For parts which are purchased, it is less important to take optimal batch sizes into account. However, prices of purchasing products may be dependent of batch sizes as well. In that situation, taking batch sizes into account for purchasing may be beneficial. If the price of purchasing parts is dependent on the batch size is dependent on the type of price.

Three types of prices are present at purchasing, namely contract prices, staffel prices and basic prices. In case of contract prices, agreements are made with suppliers about prices and minimum supply. In case of staffel prices, prices are dependent on the batch sizes and in case of basic prices, the prices are the same for all batch sizes.

In case of staffel prices, in certain batch sizes products can be ordered cheaper for price per product. In general, lower prices can be demanded when agreements for purchasing per year are made, which is the situation of contract prices. In this situation, the purchase price can be agreed independent on what will be ordered when, as long as the yearly agreement is met. The different types of prices are shown in figure 5. The relationships of price information with the ERP system and PLM are explained in section 2.4.

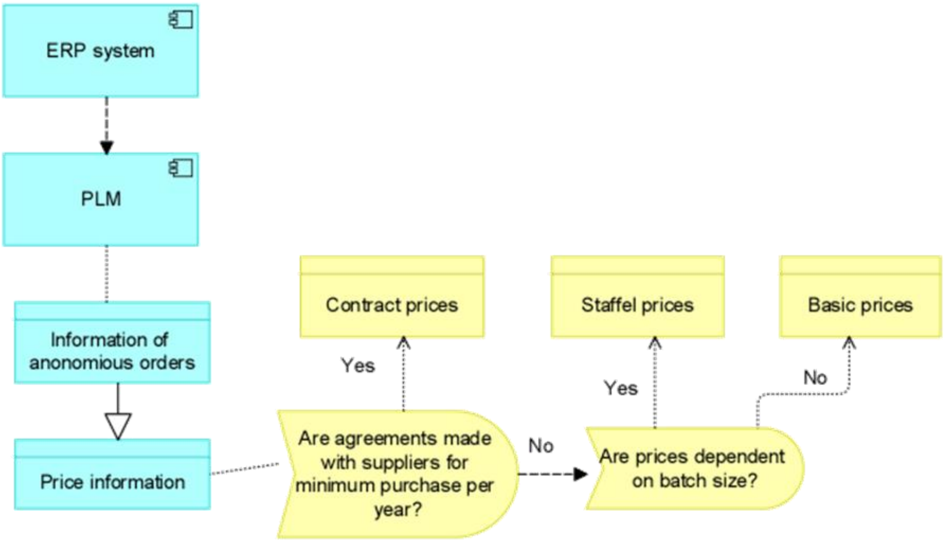

Figure 5. Different types of prices

2.1.4. Planning organized

The objective of going for efficiency by producing in optimal batch sizes or the objective of minimizing stock levels by only producing the demanded order size is taken into account in the planning. When future demand can be forecasted, the expected demand of parts, for which the demand is sufficient enough to have a small stock level, is divided over time in optimal batch sizes.

Scheduling of products, which are sold regular, is done by the planning methodology MPS. These parts are in general critical products with a long lead time, which require much machine capacity. In general, it is desired to produce critical products by the department itself. For these parts it is beneficial to have some stock. Since it is possible to have stock, more flexibility in production is available. In this case, production can be done in more optimal batch sizes. Moreover, by the existence of this flexibility, more critical products can be produced in case of available capacity and less critical products can be produced in case of less available capacity.

Furthermore, in case of holiday periods, products which can be produced by unmanned production hours can be planned more during holidays, while products which requires manhours can be produced more after holiday periods. Moreover, in case of maintenance actions, more production can be planned in the weeks before maintenance. However, the drawback of MPS is that the planning has to be filled, adjusted and cleared out by hand. Since in the current situation much products are planned by MPS, planning is time consuming. MPS gives advices, which have to be taken over by hand to production orders. If advices change, the planning has to be adjusted by hand.

On the other hand, for MRP and PRP advices fluctuate with demand. In case of parts which are planned by MRP, advices are filled by the Supply Chain department based on MPS and the Parts Manufacturing department schedules production orders by MRP. 2 weeks before production will start, advices are converted into production orders. Before converting, only the date and the amount of parts in an order have to be checked. For products produced by MRP a small number of stock is acceptable if that is beneficial for more optimal batch sizes, while for PRP products, the production should be exactly the same as demanded. Besides higher costs for less optimal production series, disapproval is more expensive for PRP products because of lower quantities.

Besides the regularity a system/part/product is sold, the pgp phase in which a product is situated may be related to the fact if a small stock level is possible or not. If products are regular sold and situated in the volume production phase, planning is done by MPS. If a product is sometimes sold and/or situated in the pilot phase, planning is done by MRP. And if a product is rarely sold and/or a new project, planning is done by PRP.

During planning, capacity limitations of machines have to be considered, while capacity limitations are not considered in the current ERP system. Therefore, Excel is used to control the planning of the production process. In Excel overviews of machine loading are shown. Based on data of the day before, these overviews are updated during night. The overviews show available machine capacities, scheduled required machine capacities and if capacities are exceeded or if capacity is left. Rescheduling is done based on these overviews. Besides updating these overviews during night, data, which is adjusted by hand in the ERP system and in Excel, is updated every 20 minutes in the overview.

The available capacity for production consist of both machine capacity and available man hours and is based on forecasted capacity, which is based on the average number of hours worked in the last 8 weeks. Planning of man hours is done by hand. Moreover, every month an investigation of capacity planning is done, which shows among others what products are running, what processes are outsourced and what the differences between capacity demand and available capacity are.

Besides an investigation of capacity planning, simulations for capacity planning are done. Based on capacities of machines and the expected demand, the available operation hours of machines and the expected demand of operation hours are compared by simulations. In this way, mismatches are plotted and insights are obtained what products causes planning problems. Based on this information, on strategic level, decisions can be made if machine capacity should be expended or what products or process steps should be outsourced.

Since stock is minimized and for some products even undesired, the planning of the department is driven on make-to-order for flow products and driven on engineer-to-order or even design-to-order for new projects. Existing projects are somewhere in between make-to-order and engineer-to-order, since some adjustments and improvements are required in the engineering part and further it follows make-to-order.

The engineering part of projects are called work preparation tasks in the processes of the department. Work preparation/ Engineering tasks which have to be performed by Factory Engineering and programming. Capacity required for work preparation tasks are dependent on man-hours capacity. Capacities of Factory Engineering, Quality Engineering, Quality Control and programming are all fully dependent on available man hours.

2.1.5. Preparation tasks organized

Preparation tasks are managed and controlled by the sections itself. Both Factory Engineering and programming plan their own tasks.

Tasks which have to be performed by Factory Engineering during work preparation are among others determining the routing and creating the routing in the ERP system, criticizing costs and discuss these costs with Cost Engineers and Sales, preparing documentation including important information, such as sizes and names, making procedures, making decisions about quality requirements, determining required material and add this information to Teamcenter, preparing measuring reports and mapping required programs and discuss these with programming. Flows of the processes in preparation tasks and its interrelationships are partly shown in figure 6.

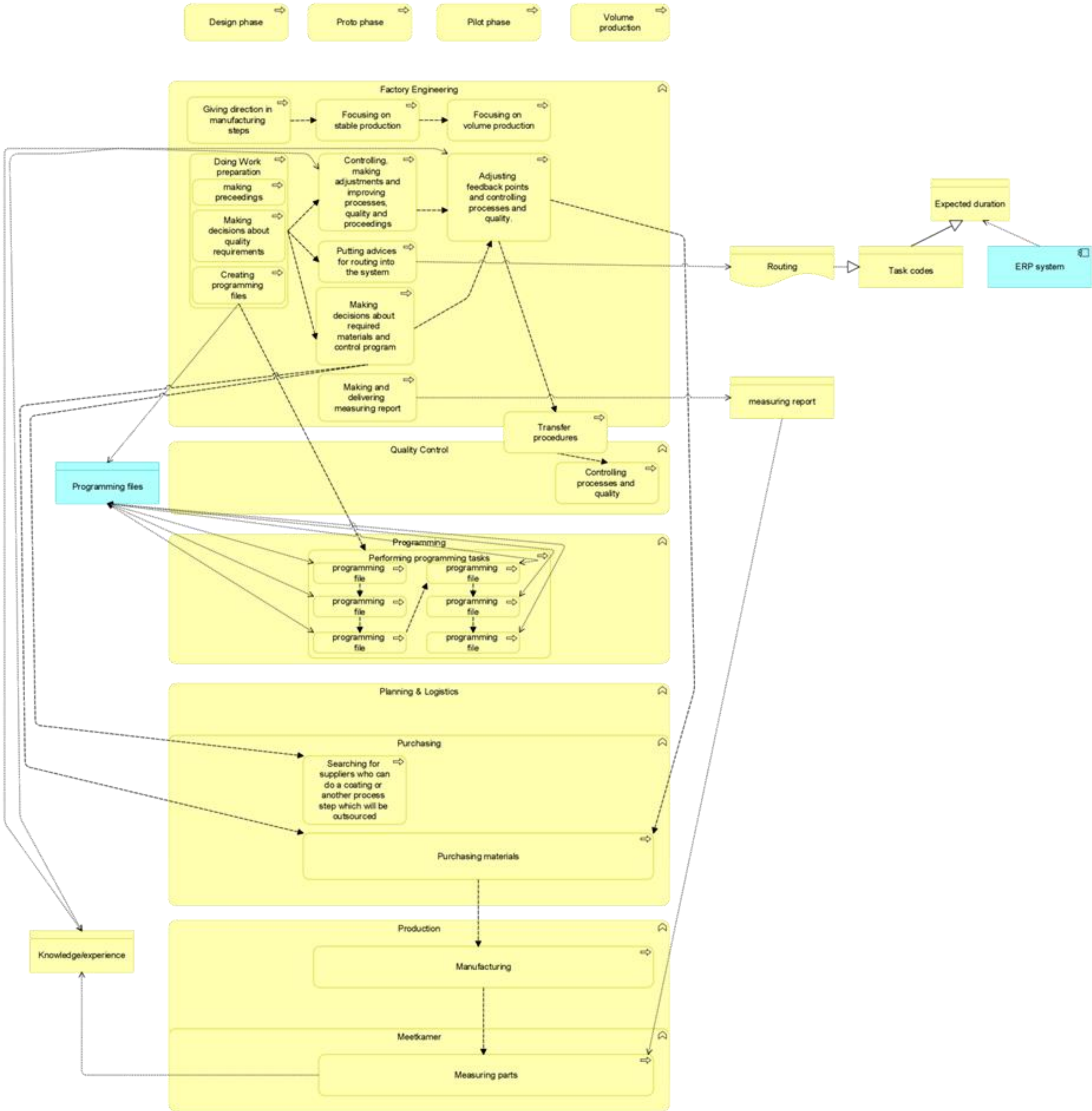

Figure 6. Process preparation tasks

In general, it does not matter in what sequence the tasks of the preparation trajectory are performed, as long as programming can start on time with programming and purchasing can purchase materials on time. For example mapping required programs and discuss these with programming is a predecessor for programming tasks, which means that programming can only start when the required programs are mapped and discussed.

After Factory Engineering have discussed the required programs with programming, CAM engineers book hours for programming the required programs. The time booked for programming the required programs is dependent on the order. Programming programs for small orders can be done in 1 week, while programming programs of big orders take half a year. Besides booked time for programming new projects, in some situations, more programming time is planned in later phases for improvements and adjustments. However, the required time for improvements and adjustments are hard to plan, since processes consist much uncertainties.

After information about required materials are added to Teamcenter, purchasing can start with purchasing materials. Moreover, when information about required materials or required proceedings is available, purchasing can search suppliers for outsourcing production steps.

For scheduling the tasks, Factory Engineering uses two different planning tools, namely MS projects and Gannt charts in Excel. Which planning tool is used, is dependent on the complexity of the project. MS projects is used for the more complex projects, since MS projects is capable to give information about among others critical resources, critical process routings and control/check points.

In the current situation, planning preparation tasks is done in other systems than in the ERP system, since the ERP system works with quite precise estimations and the durations of the work preparation tasks are unpredictable. For the same reason, the forecasts of the durations of these tasks are even not connected to the ERP system. The planning of Factory Engineering is taken over in the planning for manufacturing.

According to the head Factory Engineering, keeping updating the ERP system for unpredictable activities is waste. Therefore, in the current situation, Excel is used to report the progress. Reporting the progress is done to check if Factory Engineers are on time, the reason of being not on time and what do Factory Engineers need. The reported progress is communicated to logistics, such that manufacturing can be (re-)scheduled.

In the current situation, the booked hours for programming and its progress is not visible for manufacturing. The head programming asked for an interface in the ERP system where booked hours could be registered, but for the current ERP system it is hard or very expensive to get such an interface.

The planning made by Factory Engineering is used for among others checking when Factory Engineers have space for a project, when projects are scheduled and to which Factory Engineer a project is assigned. For older projects, preparation tasks are significant smaller than preparation tasks for new projects. While preparation tasks of new projects may have a duration of a couple of months, the duration of work preparation tasks of older projects requires only a couple of days. Therefore, in the planning to check when Factory Engineers are available, only new projects are scheduled and older projects are left to work on in buffer time. However, in this situation, it is unclear when tasks of older projects have to be done and available capacity for these older projects is a bottleneck. The buffer time reserved per engineer is around 10% of the time, in which preparation tasks for these older projects can be performed.

To illustrate the manner in which work preparation tasks of an older project may be organized, project 7322 324 81038 (LS X body) is used as an example. For this project, a modification was required, for which work preparation tasks were required from both Factory Engineering and programming. The duration of tasks of Factory Engineering was around 13.5 hours and the duration of programming tasks was around 1 day.

While, the duration of work preparation tasks of Factory Engineering was in total 13.5 hours and of Programming around 1 day, the lead time of the work preparation trajectory for this project was around 4 weeks. The lead time of the work preparation trajectory was significant longer than the duration of tasks, since both FE and programming were busy with projects with a higher priority. However, since it was a small job, this project is performed somewhere in between, while capacity was not left.

Work preparation tasks for this project of Factory Engineering are shown below with its corresponding duration, predecessor and successor:

Tasks Factory Engineering preparation trajectory:	Duration tasks (in hours):	Predecessor:	Successor:
Criticize costs in ERP system and discuss costs with Cost Engineer and Sales	6		
Mapping which programs require modifications and create a production order, such that programming can reserve hours	2		Programming can start
Add missing information of material, which should be available in Teamcenter	1	Purchasing indicates that information is missing	Materials can be purchased
Overhaul documents and modify sizes, names and other important information	4		
Checking routing + releasing routing	0.5	Programming should be finished + all preparation tasks should be finished	Production can start
Total	**13.5**		

2.1.6. Production organized

Production is responsible for performing the process steps and controlling the warehouse. While Production controls the warehouse, Logistics is better informed about what is going on at the warehouse. Therefore, management of the warehouse is seen as a grey area.

Processes at the workfloor consist of multiple process steps, which are performed by different production sections. Since it is difficult to measure the performance of each separate production section for every order, one production section is selected as the responsible section. The responsible section is selected based on the proceedings performed for the order. The performance of an order is measured for the responsible section of that order. The responsible section is mentioned in the product portfolio of the order. This is shown in figure 7.

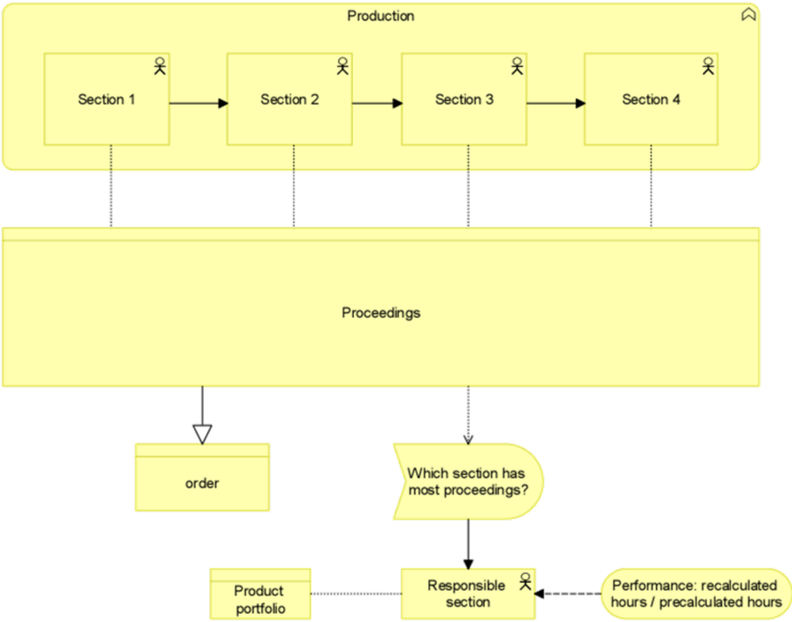

Figure 7. Responsible section

In general, production is organized in such a way that materials are delivered, settings for machines are set up and tools are collected before operations are performed. After operations are performed, some benchwork is done, products are washed to make it fat free and products are measured. If measures of the products meet requirements, a surface cleaning is done.

During production 3 types of tools are used, namely clamping jigs, bites and carts. At multiple machines bites are used, especially at milling operations, many different tools are used. At some milling operations, even 40 different bites are required. In the current situation, required tools are communicated during Excel files and by a briefing given by Logistics. Moreover, packages which are required, are requested by a Kanban system. The availability of bites and carts are not visible, while the availability of clamping jigs is visible, since clamping jigs are reported in the current ERP system.

2.1.7. Quality organized

Quality Engineering is responsible for controlling quality. Controlling quality is done by checking documentation, handling complaints and managing a recovery strategy when failures are observed. By checking documentation, QE validates if documentation satisfy requirements and whether enough effort is done to minimize production risks.

Both the intern proceedings and process steps which are outsourced have to meet customer requirements. Relations between procedures, customer requirements, intern process steps, Quality Engineering, Factory Engineering and outsourcers are shown in figure 8.

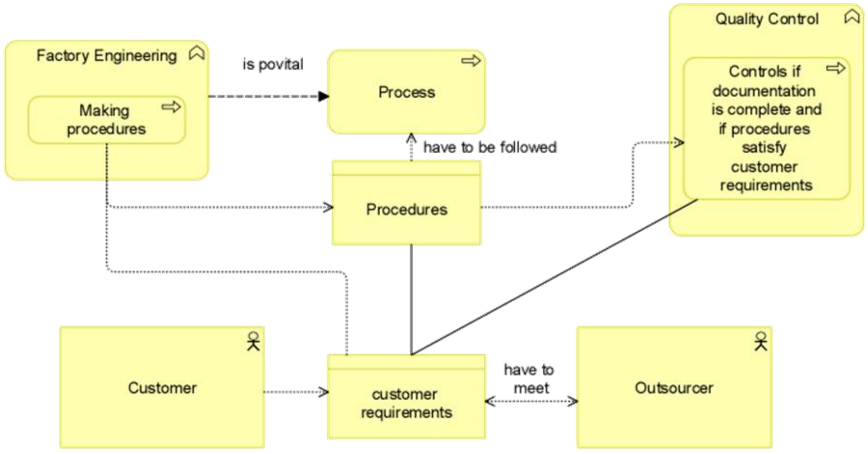

Figure 8. Customer requirements and its relationships

Checking documentation is desired for both production orders and purchasing orders. In case of production orders, checking documentation and giving approval for new projects before production can start is done since last year by Quality Engineering. Before, documentation prepared by Factory Engineering was not checked by Quality Engineering. The process of checking and approving documentation by Quality Engineering is called APQP. Desired APQP control moments are at TPD review, pre-programming, pre-production, proto-evaluation (release for pilot phase) and pilot-evaluation (release for volume production). In the current situation, APQP control is not done for projects which are produced before APQP control was introduced into the company, while these projects may need modifications and work preparation tasks.

In case of purchasing or outsourcing orders, it is desired to check documentation of suppliers/outsourcers before a purchasing order is placed. However, in the current situation, documentation is often even not received before a purchasing order is placed.

Intermediate checks are even more desired, since checking and approving documentation became more important since Zeiss is a customer. Since Zeiss is a customer, Quality Engineering is more explicit working on intermediate checks for checking supplier documentation. Supplier documentation, which will be checked and approved by Quality Engineering, is received by mail from the supplier, inserted by hand in CAQ, such that it becomes available for Quality Engineering. This process is shown in figure 9.

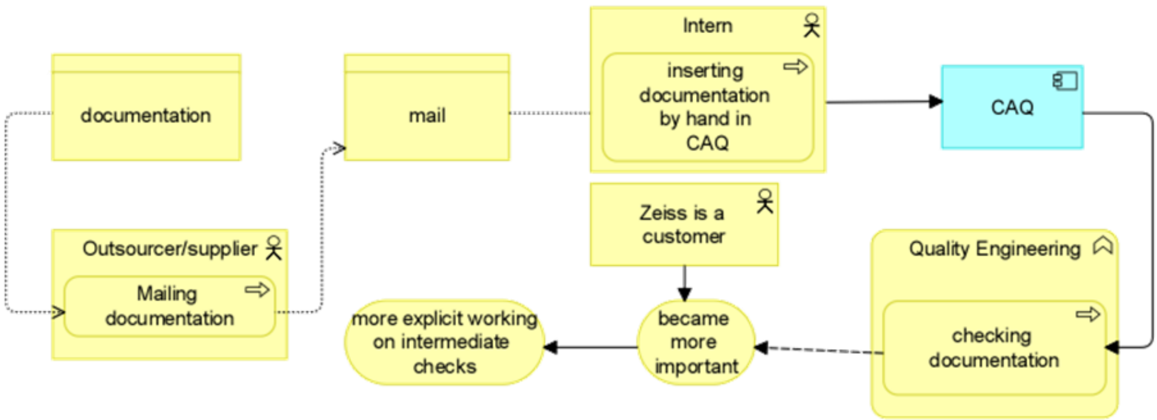

Figure 9. Process checking supplier documentation

Documentation should contain quality specifications and how these specifications should be met by the processes. By measuring parts, documentation is used to check if specifications are met. Quality specifications may modify over time, which may cause in multiple versions of documentation. Therefore, it is desired to choose which quality document should be used. However, in the current situation, new quality documents cannot be forwarded if quality documents are already forwarded. It is desired to have the ability to save and update quality documents and to make choices about using the most recent version or another version of the quality documents. It is desired that a version of quality documentation can be chosen before measuring values are registered.

Modifications in quality documentations may include modifying sizes and modifying ranges of granted deviations. The degree in which deviations are granted is dependent on the High Impact Part (HIP) rating of an product. Parts with a high HIP rating have less strict specifications than parts with a low HIP rating. If the HIP rating is high, small changes are more likely to be accepted than if the HIP rating is low. In figure 10 the HIP rating is shown.

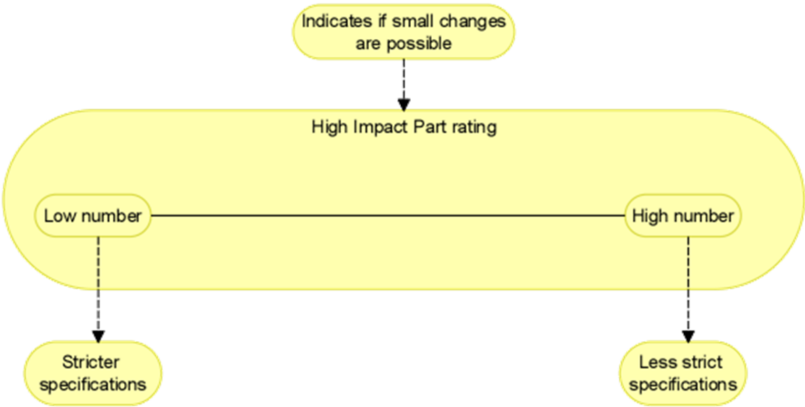

Figure 10. HIP rating

Besides the degree of strictness of specifications, the degree of deviation is an important factor for granting the deviation or not. In case of deviation, the deviation is first evaluated and if the deviation seems to be acceptable, a concession is requested to the customer. Moreover, a procedure is started to research how the deviation can be prevented for new orders. The result of a concession can be that the deviation is granted, disapproved or repaired. In case of a small deviation, the deviation may be accepted by the customer. In that situation, the deviation is granted and the production process may be continued, dependent on the reason for deviation.

In case of a bigger deviation, it is dependent on repairability of the deviation if the deviation will be repaired or disapproved. If the deviation is disapproved, the part will be scrapped, materials will be ordered again and production will start again. If a deviation is repairable and the result of the concession is that the deviation will be repaired, rework will be done. During asking concession, a recovery strategy is proposed to the customer if the deviation is repairable. Rework, which will be done if the deviation will be repaired, should be in line with the proposed recovery strategy.

Independent of the result of the concession, production is interrupted during asking concession and have to start up again after the customer has reacted to the concession. If deviation is granted, the remaining production process has to start up again, if deviation will be repaired, the process for performing rework according to the recovery strategy will start up and if deviation is disapproved, a new order for the corresponding part will start up. Planning starting up a process after concession is done in consultation with logistics.

Interrelationships with regard to deviations and concessions are shown in figure 11.

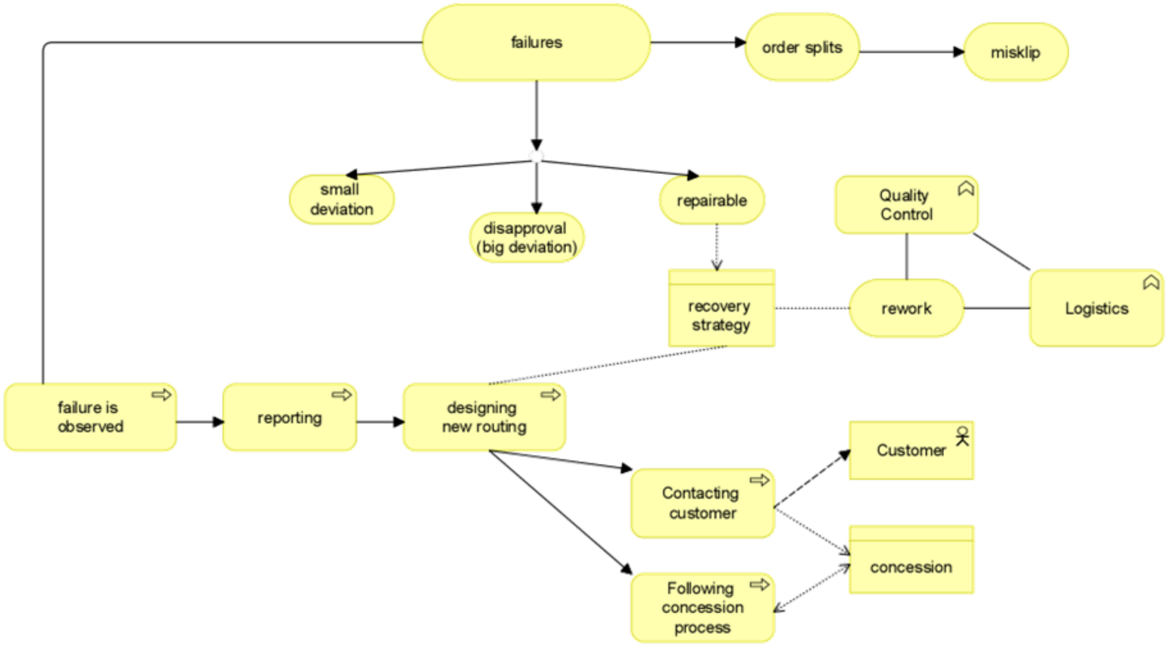

Figure 11. Deviations and concessions

During the processes, parts are measured by Quality Control and checked if the actual dimensions of the product are in line with the specifications of the documentation. Products which need to be measured are send by the ERP system and printed by Quality Control. Quality Control intends to plan orders which need to be measured as good as possible. However, with the information given by the current ERP system, planning is hard according to the head of Quality Control.

At the moment a failure or deviation is observed or measured, the failure/deviation is reported. Reporting failure/deviation is done in two systems, namely the ERP system and CAQ REM. The ERP system is used for controlling logistic processes and CAQ REM is used for controlling complaints. If a failure is reported, the process step at which the failure has occurred is reported into the ERP system and the failure itself is reported in CAQ REM. Data of both systems are exported to iQbs in Excel, which will be used to manage orders containing deviations on products. When a failure/deviation is reported, it is indicated by inserting “1” into the ERP system. All orders which are indicated by “1” are on a quarantine list. The quarantine list consist of orders for which actions needs to be taken and of orders which are waiting on actions to be taken, such as rework, investigation or approval by the customer. These orders are not visible in the ERP system, which results that these orders are lost.

In figure 12, relations of controlling failures and systems in which failures are reported are shown.

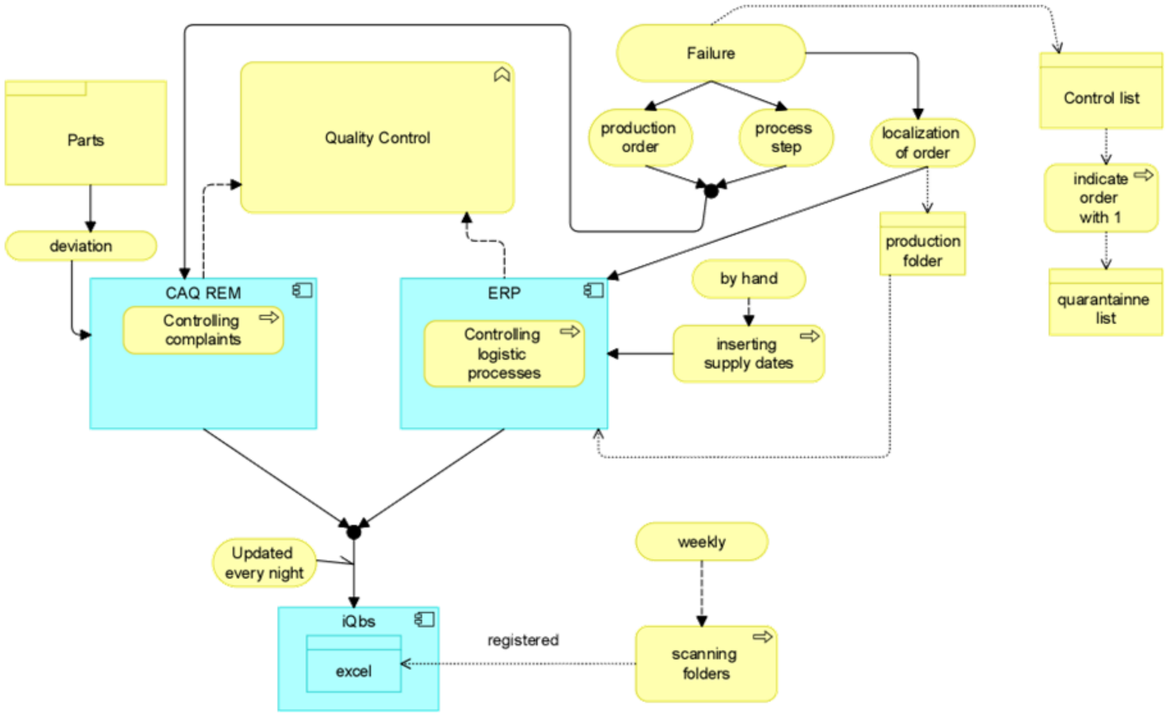

Figure 12. Relations of controlling failures and reporting failures into CAQ REM and ERP system.

Besides observing failures intern, failures can be observed and disruptions occur at suppliers and outsourcers. If a failure is observed or disruption occurred at an outsourcer or supplier, it is reported in the Q-portal. In case of failures and deviations, the remaining process is discussed and a research is started to find out the cause of the failure.

2.1.8. Logistics organized

Logistics is organized in such a way that it intends to control production orders and to optimize future intern and outsourcing work loading. Logistics is responsible for the planning of orders, ordering materials on time and controlling production orders. First of all logistics makes a planning based on the output of the ERP system. Subsequently, when materials should be purchased, logistics gives approval for purchasing materials. Moreover, when an order is ready for production, which means that work preparation tasks are finished and materials are received, logistics is responsible for releasing orders. Furthermore, logistics is responsible for controlling the production orders during production.

During planning of orders, first the demanded delivery date is checked if it is feasible. If not, the customer will be contacted to agree on another delivery date. Besides agreeing another delivery date, in case of multiple customer orders, agreements about other order sizes in case of multiple products/orders may be made.

To illustrate, article 7322 324 81038 (LS X body) is used as an example. This article is produced in the past, however, a modification is required in the production or milling program. The modification done for this article is modifying a functional geometry. For this article 1 product is requested per week for a total of 15 weeks, from which the demanded delivery date of the first product is the 1st of march. Customer orders for this article are placed on the 23th of December 2020. Due to Christmas holidays of employees of the company itself and of suppliers, the project could at first start from the 1st week of January.

In the current situation, only the lead times of purchasing (leadtime of materials) and production, are considered. The total lead time of these sections together is 3 + 5.6 = 8.6 weeks, which means that if the production of this article would start in the first week of January, delivery of products of this article cannot be before the end of week 9. Therefore, the demanded delivery date of the 1st of march is not feasible, since the 1st of march is in the beginning of week 9.

Since a modification is required for this article, it is desired to start with a small order, such that the modification can be validated and improvement actions can be performed if mistakes are found, before the remaining order is produced. Based on advices given by the ERP system, production orders of the following batch sizes and due dates are planned to produce:

Order number	Sample size	Due date
259010	1	19-03-21
259011	2	19-03-21
259012	2	09-04-21
259013	5	30-04-21
259014	5	04-06-21

If agreed delivery dates are not adjusted for this article and above mentioned due dates for production orders are considered, scheduled delivery of products should be continuously in backlog.

The expected backlog if delivery dates are not adjusted are shown below:

date	week	demand	production	Inventory (on Monday morning)	Inventory (on Friday evening)	Backlog (on Monday morning)	Backlog (on Friday evening)
01-03-21	9	1	0	0	0	1	1
08-03-21	10	1	0	0	0	2	2
15-03-21	11	1	1 + 2 = 3	0	0	3	0
22-03-21	12	1	0	0	0	1	1
29-03-21	13	1	0	0	0	2	2
05-04-21	14	1	2	0	0	3	1
12-04-21	15	1	0	0	0	2	2
19-04-21	16	1	0	0	0	3	3
26-04-21	17	1	5	0	1	4	0
03-05-21	18	1	0	0	0	0	0
10-05-21	19	1	0	0	0	1	1
17-05-21	20	1	0	0	0	2	2
24-05-21	21	1	0	0	0	3	3
31-05-21	22	1	5	0	1	4	0
07-06-21	23	1	0	0	0	0	0

Since it is undesired to have backlog, other delivery dates are agreed in consultation with the customer. Moreover, for efficiency reasons and for minimizing intern inventory levels, full production order sizes are communicated to deliver simultaneously instead of 1 product per week. Therefore, the following delivery dates and sizes are agreed with the customer:

Delivery date	Size of delivery
19-03-21	3
09-04-21	2
30-04-21	5
04-06-21	5

For this project, production order 259010 and production order 259011 have the same due date and are delivered together. Production of these orders can be performed partly simultaneous, while it is intended to start production order 259010 a bit earlier. Especially for the last machining, it is important that production order 259010 is performed first, since the last machining has to deal with accurate sizes, which include most risk. After measurements are done and agreed for production order 259010, the last machining can be performed for production order 259011. After measurements on production order 259011 are done, a surface treatment for both production orders 259010 and 259011 is performed.

The date on which production is scheduled to start, the date on which production should start at or before to meet the due date and the date before which materials should be ordered to meet the scheduled production date are shown below:

Order:	Order size:	Due date:	Production should start before:	Production is planned to start on:	Materials should be ordered before:
259010	1	19-03-21	09-02-21	02-02-21	12-01-21
259011	2	19-03-21	09-02-21	04-02-21	14-01-21
259012	2	09-04-21	02-03-21	15-02-21	25-01-21
259013	5	30-04-21	23-03-21	17-02-21	27-01-21
259014	5	04-06-21	27-04-21	03-03-21	10-02-21

For production order 259010, the earliest start times, the earliest finish times and the due date of production operations according to the scheduled start of production and the due date of the order are shown below:

Order position	Cumulative planned lead time rounded up (in days)	According planning can start earliest on:	According planning can be finished earliest on:	Operation should be finished before:
10	11	02-02-21	17-02-21	24-02-21
20	11	17-02-21	17-02-21	24-02-21
30	16	17-02-21	24-02-21	03-03-21
35	17	24-02-21	25-02-21	04-03-21
40	19	25-02-21	01-03-21	08-03-21
50	20	01-03-21	02-03-21	09-03-21
60	27	02-03-21	11-03-21	18-03-21
70	28	11-03-21	12-03-21	19-03-21

However, at the 9th of march, production is running behind planning. While according to the planning, the progress of order 259010 at the 9th of march should be performing production operation 50 or 60, production operation 40 is performed at the 9th of march. Since production operations are only reported when the operations are finished, the progress of operation 40 at the 9th of march is not visible.

Dependent on the actual progress of production operation 40, finish times of operations and expected lateness can be estimated. In the table below the expected finish times of the operations are shown:

Order position	Planned lead time (in days)	Operation should be finished before:	Based on progress, operation can be finished earliest on:	Based on the progress, operation can be finished before:
40	1.31	08-03-21	09-03-21	11-03-21
50	1.03	09-03-21	10-03-21	12-03-21
60	7.00	18-03-21	19-03-21	23-03-21
70	1.10	19-03-21	22-03-21	24-03-21

As a result, the expected lateness is half a week.

When delay has occurred during production and the expected lateness is estimated, the customer will be informed.

2.2. Processes

According to the manager of the Parts Manufacturing department are production processes at VDL ETG Almelo long, complex and diverse. Especially the more complex products require many steps and a long routing. Routings for manufacturing are generated in the ERP system by Factory Engineers. Since processes are complex and diverse, planning of the processes is difficult. Especially, planning the preparation tasks is experienced as difficult by stakeholders of the department. Work preparation tasks are dependent on various factors, such as the maturity of manufacturing process design of the project, the available capacity and the expected lead times of the project. The maturity of manufacturing process design of a project is guided by the product generation process (pgp) and describes among others if the project is ready for stable production and/or volume production. The available capacity is dependent on the number of FEs and CAM engineers and the availability of these engineers. The expected lead time of a project is dependent on the type and complexity of the product.

While, preparation tasks of projects are dependent on the pgp status of the project, available capacity and expected lead times, almost all projects follow the same process. This process is shown in figure 13. Work preparation starts with checking customer requirements on feasibility. If the requirements are feasible, other work preparation tasks can be continued. Otherwise, feedback is given to the customer and tolerances are adjusted before other work preparation tasks will be performed. Work preparation tasks are performed by FE, programming (CAM engineers) and purchasing. First preceding tasks for programming and purchasing have to be performed by FE before programming and purchasing can perform tasks. In case of new projects, a quality check is performed by QE to validate documentation after work preparation tasks are finished. After approval of QE based on the quality check, production can start. Subsequently, products are checked if the customer requirements are met. If the requirements are met, products are delivered to the customer and the article is reviewed on maturity. Otherwise, decisions for the further process have to be made in agreement with the customer. In figure 13, the possible decisions and the corresponding flows are shown.

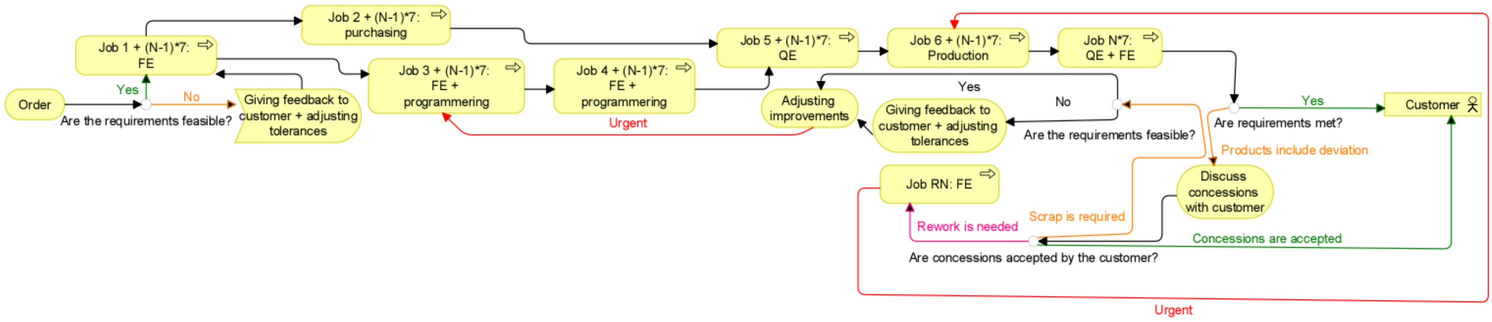

Figure 13. General process of projects including flows due to deviations

2.2.1. Product Generation Process (PGP)

For project management at the department, the pgp process is an important process, since it describes the maturity of an article and the project phase to which the maturity of the article belongs. In figure 14 the considered phases of the pgp process are shown. The considered pgp process phases are concept, design, proto (test), proto (adjustment), pilot and volume production. In general for new projects, first a request is placed by the customer before a real order is placed. For existing products, marketing and sales are in contact with the customer to get indications of forecasts for future orders. It is intended that both requests and forecasts are later on replaced by orders. However, requests and forecasts are not always replaced by orders.

At the moment that an order is placed, the ERP system gives a first article inspection (FAI) notification if the product is a new project or if the product is not produced for more than a year. In other situations, it is verbally agreed to what phase an product belongs, while it is desired to have ERP data to what phase products belongs. Besides a notification for new projects and products which are not produced for a while, it is desired to get a trigger for products in the pilot phase as well.

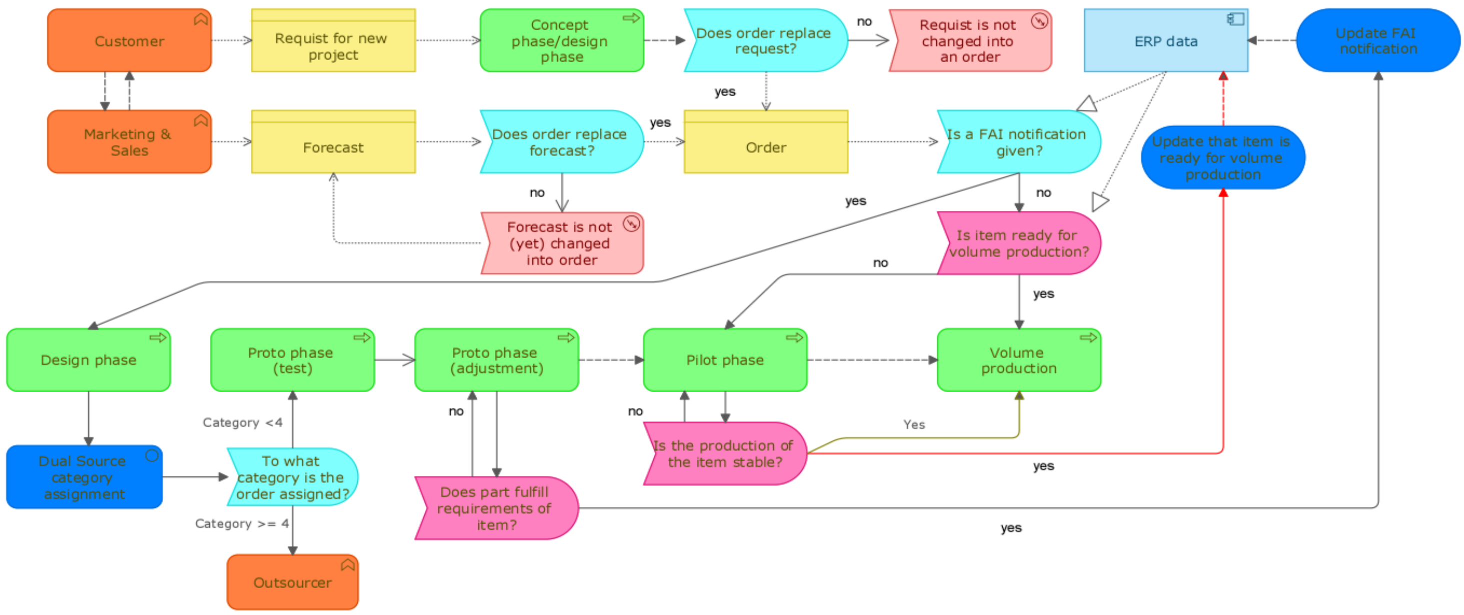

Figure 14. Determine the maturity of the manufacturing process design of a product

While a FAI notification is given by the ERP system, the ERP system does not indicate if an product is ready for volume production or not. In figure 14, decisions which are made by the ERP system are light blue colored and decisions which are made verbally are pink colored. Therefore, “Is a FAI notification given?” is light blue colored and “Is product ready for volume production” is pink colored in figure 14.

For deciding if the product is ready for volume production, it would be beneficial if comparable data is available for indicating if the product is ready for volume production and that this data can be updated in a similar manner as updating the FAI notification. Updating the FAI notification is done after the product fulfills its requirements after the proto phase. It is desired to update that a product is ready for volume production if production is stable after the pilot phase. Both, “update FAI notification” and “update that product is ready for volume production”, are dark blue colored in figure 14, which means that ERP data is adjusted and/or added.

While most products go through a transition of pgp phases, some products do not experience the transition from proto to pilot to volume production. Article 7322 324 81038 (LS X body) is one of these products. A couple of products of this project are produced in the past, however, production processes are changed over years. Because of these changes, the maturity of manufacturing process design have to be checked and modified.

Besides indicating in what pgp phase a product belongs, the expected duration of such a generation phase and the expected duration of performing work preparation tasks of an product are important factors for planning processes. For products in pilot phase forecasts of expected durations can be made more precise than for products in proto phase. Forecasts for the duration of the proto phase are roughly estimated, while forecasts for the duration of the pilot phase are based on the actual duration of the proto phase. However, during the proto phase often interruptions occur, which causes delay and requires controlling effort of FE and logistics. Furthermore, the forecasted duration of performing work preparation tasks for a specific product is dependent on the expected lead time of producing that product.

Products which belong to the pilot phase follow continuously a loop of modifying and improving previous procedures until the production of that product is ready for volume production. While it is unknown how many adjustments are required before production of a product is ready for volume production, in general, required adjustments are becoming smaller after each loop.

Durations of the proto and pilot phase and the process for forecasting the durations of performing work preparation tasks are shown in figure 15.

Besides estimations for durations of tasks which can be made more precise in later phases of the pgp process, products which belong to earlier phases of the pgp process require in general longer preparation tasks. Later on in the pgp process, preparation tasks are shorter since only modifications/improvements have to be performed as work preparation, which is less time-consuming than work preparation for new projects.

Moreover, forecasts can be made for flow products, while for projects it is barely to not possible to forecast when and how many products of an product are demanded. Therefore, products which belong to earlier pgp phases are relatively late known. Meanwhile, it is expected that these projects are delivered on time. Combining a longer preparation trajectory and relatively late arrival of orders, results that these projects are seen as last minute projects, which requires actions soon. In general, capacity is left in the planning for these kind of last minute projects.

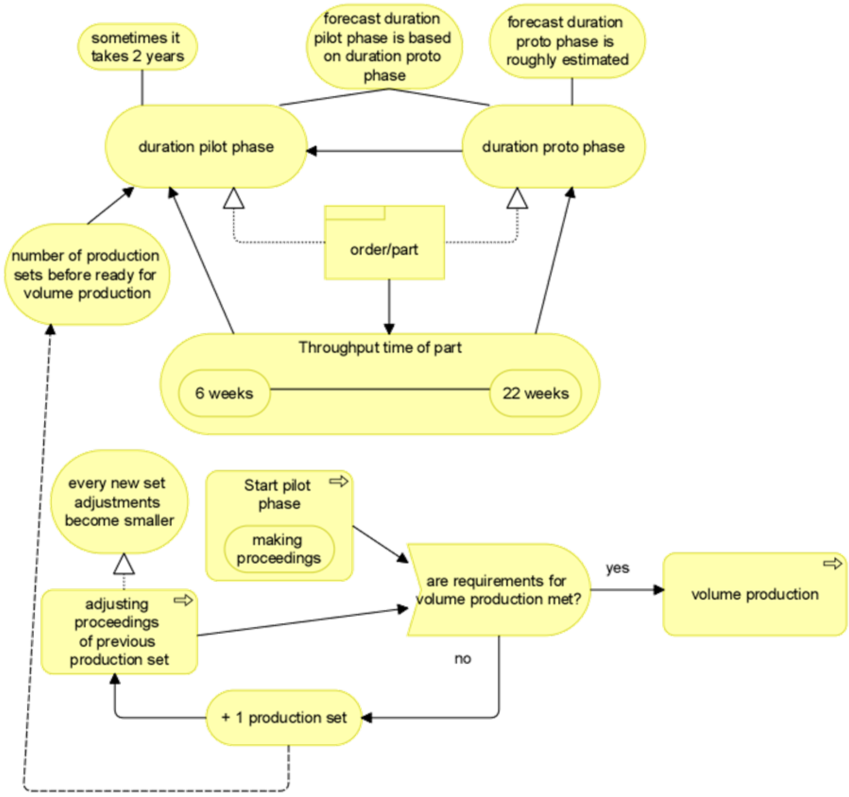

Figure 15. Durations pilot and proto phase

Besides, forecasts for projects can barely be made, projects are often one-off. Flow products, for which forecasts can be made pretty well, are called flow products. Besides the forecasts which are pretty precise, even variation of demand can be investigated for flow products. Flow products are products which belongs to the volume production phase. While flow products flows flexible through the processes, projects are more sensible to disturb the processes.

Flow product orders at the Parts Manufacturing department are filled top down, which means that forecasts are inserted into the system by Sales and balanced over time by Supply Chain by using Master Production Scheduling (MPS).

At the Parts Manufacturing department, flow products are the more important and larger parts to produce. These flow products are produced by a stable move rate, such that a stable production plan can be followed. These parts require much capacity in terms of both machine capacity as storage area and follow a leveled production plan. Unless the stable production, these products cause much disturbance in the current situation, since the Assembly department and the Parts Manufacturing department are not aligned enough.

Processes at the Assembly department are significant later than the processes at the Parts Manufacturing department. Since the Assembly department is more focused on their own processes and less on the overall processes, demands are specified when processes at the Parts Manufacturing department are in progress or already finished.

When it is required what the demand is from the Parts Manufacturing department, demand is given in big buckets. While orders ordered by the Assembly department are given in big buckets, only 1 product is required per week. If these orders are delivered separately to the Assembly department and the order is partly coming later than the demanded delivery date, the status of the order in the

ERP system indicates that the order is in backlog. While, delivery is not required yet, the system indicates that delivery is late. As a consequence of big buckets of demand, disturbance occurs in the processes, since manufacturing takes longer and other orders are waiting.

Besides a difference between flow products and projects, products can be divided into standard products and products which are dependent on multiple factors. Automation of the processes of standard products is possible by a computer controlled program. Moreover, lead times can be forecasted well for standard products. Production processes of products which are dependent on multiple factors, contain much variability. These processes are among others dependent on operators and other operations of the process.

Different types of products and its characteristics are shown in figure 16.

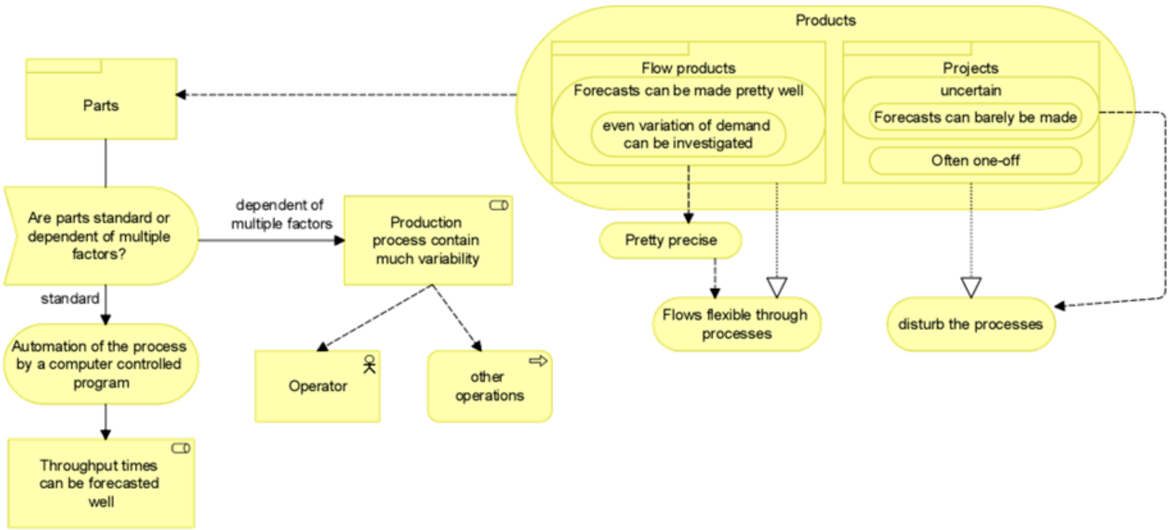

Figure 16. Different types of products

2.2.2. Dual source process

Besides differences in flow products and projects and differences in the maturity of manufacturing process design of products, differences exist in the required technology for producing products. Based on the required technology for producing a product, a category is assigned to that product in Dual Source category assignment.

During Dual Source category assignment, a category is assigned to the product which indicates if the product should be manufactured intern, should be outsourced or could be both manufactured intern and outsourced. The category which is assigned to the product is captured into the ERP system. Categories are assigned to products, such that the furnished Supply Chain meets the expectations of both the customer and the company in terms of Quality, Logistics, Technics and Costs (QLTC).

The assignment of categories is captured in 5 categories, which are high-end technology, medium technology parts, medium technology compositions, simple technology and purchasing technology. Category 1 includes high-end technology, for which it is decided to always manufacture intern because of strategic reasons. Category 2 includes medium technology of parts, for which manufacturing can be done both at the parts manufacturing department and manufacturing can be outsourced. Category 3 includes medium technology of compositions, for which manufacturing can be done both at the assembly department and manufacturing can be outsourced. Category 4 includes simple technology, for which it is decided to outsource it always because of price-technical reasons. Last, category 5 includes technologies which are lacking at VDL ETG Almelo, therefore, it is decided to always outsource products which require missing technology.

Products from category 1 are always manufactured intern and products of category 4 and 5 are always outsourced. Products which require medium technology, which are assigned to category 2 and 3, are sometimes manufactured intern and sometimes outsourced. For these products, the decision of manufacturing intern or outsourcing is made based on some criteria. These criteria include, the available machine loading versus budget, the customer portfolio and the system/module portfolio.

2.3. Uncertainties

Besides differences in required technologies and differences of phases to which products belong, the processes contain a variety of uncertainties. During the processes, new customer orders may arrive continuously, the arrival of new orders may deviate from its forecasts and the demanded delivery date of a customer may change during the processes. Moreover, specifications demanded by the customer, such as sizes, may change. Changes in demand and fluctuations in arrival may interrupt the processes and its planning.

Besides uncertainties in demand, uncertainties are present during the processes. Especially during work preparation tasks, the durations may deviate from the forecasted durations. Especially programming tasks require often more time than estimated. Besides the durations which may deviate from the forecasted durations, unpredictable events may occur during the preparation trajectory as well. Furthermore, unpredictable events may occur during production as well. During production, delay can be caused by among others machine failure, outsourcers which may be late and by quality deviation.

Besides uncertainties which may cause delay, uncertainties with regard to prices are present at the processes as well. Uncertainties with regard to prices are two-sided. On the one hand, prices of materials may change and on the other hand, it is not visible for what price a system is sold.

2.3.1. Forecasts

While new customer orders may arrive continuously and in some situations it is very uncertain when an order will arrive, for some orders forecasts can be made pretty well based on estimations. Forecasting of demand is done by asking customers for estimations of future demand. These estimations are asked by Sales. Consequently, if the customer has send indications of its forecasts, these forecasts are put in the ERP system by Sales.

Forecasts are reported in the ERP system for 5 quarters ahead. Forecasts for 6 or more quarters ahead are for some products available, however, these forecasts are not reported yet in the ERP system.

The forecasts are considered as the expected demand and consequently divided over time in production orders with optimal batch sizes, which are used for scheduling. Based on the actual demand, these production orders may be changed.

The process of making forecasts and converting expected demand into production orders is shown in figure 17.

Since forecasts are still expected demand and not actual demand, actual demand may deviate from its forecasts. Therefore, forecasts include uncertainty. Even for actual orders, changes in demand may occur due to modifications of the planning of the customer and/or unexpected events at the customer.

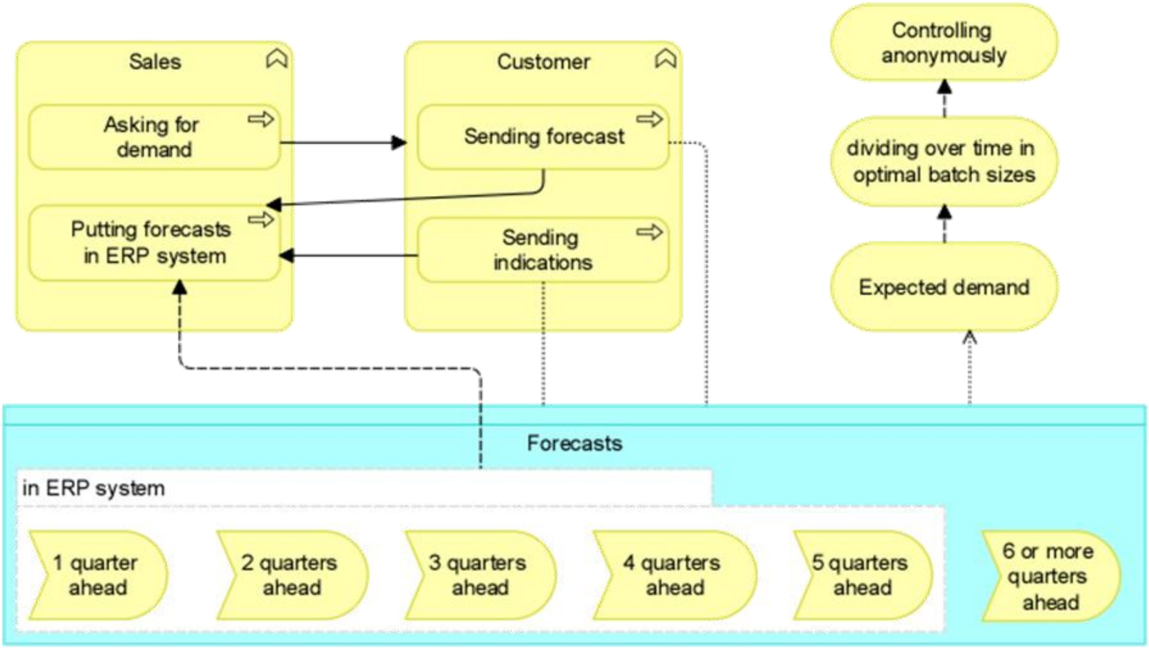

Figure 17. Forecasts

2.3.2. Unpredictable events

As mentioned before, unpredictable events may occur intern during the preparation tasks and during production. Unpredictable events during work preparation may include that materials are delivered late, which results in delay of starting production. Moreover, as an unpredictable event, information may be missing during preparation tasks. For example, for an existing project, a project situated in the pilot phase, it is assumed that information is already available, since that product is produced earlier. However, at the moment that purchasing intends to purchase the required materials, the drawing is lacking in Teamcenter, which means that information about sizes is not available. As a result, Purchasing contacts FE to indicate that information is missing. Consequently, adding information about the material in Teamcenter becomes an urgent activity for FE to make sure that purchasing material would not cause delay.

Unpredictable events during production may include machine failure, quality deviation, outsourcers which may be late and last-minute urgent tasks for products with higher priority have to be done in between, machine failure. Beforehand, due dates are agreed with outsourcers. However, unpredictable events may occur at the outsourcer, which may result in delay at the outsourcer and thus for the remaining processes as well.

2.3.2.1. Machine failure

Intern interruption may be occurred by machine failure. If a failure has occurred at a machine, that machine cannot be used until the failure is fixed. As a result, process steps which should be performed at that machine should wait until the failure is fixed or the process step should be rescheduled to an alternative machine. In case of machine failure and maintenance, production is postponed by hand in the planning. In the current situation, around 5% of capacity is left for interruptions, such that corrective maintenance can be performed.

Dependent on the type of failure, the failure is fixed intern or fixed by the supplier. In case of a small failure, the failure is fixed intern by the technical service. In general, a small failure which is fixed intern can be fixed fast, while fixing big failures, which are fixed by technicians of the supplier, may have a long duration. Fixing a bigger failure is more time-consuming since it is a more difficult to fix. Moreover, a failure which has to be fixed by the supplier of the machine is dependent on the planning of technicians of the supplier. Since, fixing a big failure is dependent on the planning of technicians of the supplier, it may occur that waiting is required before the failure can be fixed.

In figure 18, the process of machine failures and if the failure will be fixed by intern technical service or by technicians of the supplier is shown.

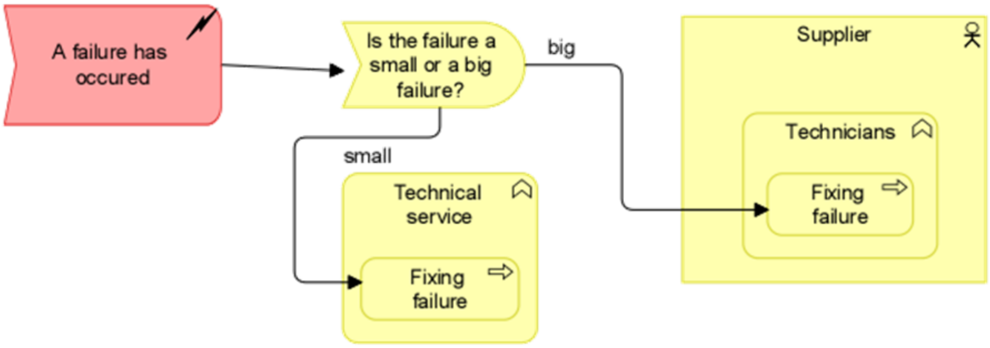

Figure 18. Machine failures

Besides fixing failures, the technical service manage maintenance. For maintenance management, technical service uses its own system. Moreover, during preventive maintenance, modifications are made by programming and FE.

2.3.2.2. Quality deviation

Besides machine failures, failures of production products may occur. If a product failure occurs, it is called quality deviation, since the quality of the product deviates from the product requirements. If a quality deviation is reported, the quality deviation is fixed if it can be easily fixed and otherwise a concession is requested from the customer. A concession includes the quality deviation and if the deviation is repairable, a proposed recovery strategy. The duration of a concession process is dependent on the response speed of the customer, which may take long. During waiting for a response of the concession request, it is uncertain what the continuation will be.

Actions which can be done are dependent on the problem and if a concession is required. If a concession is required, the possible results of the concession may be that the concession is accepted, that rework is needed or that scrap is required. Since it is uncertain what the decision of the customer will be and waiting for a decision may take long, often a new order is started up, when it is expected that scrap could be a realistic outcome, to prevent the risk of an even longer delay if parts will be rejected. However, if the concession is accepted, the new started production order will be used for a future customer order. Chances for acceptance of the concession, the need of rework and the need of scrap are dependent on recovering possibilities and the gravity of quality deviation.

To illustrate, project 7322 324 81038 (LS X body), from which recently two products came in quarantine due to two unpredictable events, is used as an example. For one product, the M3 plug is aborted and for another product, the diameter of the fitting hole was too small. The products has been in quarantine for around 1.5 to 2 weeks, since capacity was not available to control the product.

The products came in quarantine at the following moments:

Order	Date in quarantine	Reason for quarantine	Date action done	What is done	Date out of quarantine	Decision made/ action done
259010	02-03-2021	Fitting hole is too small	12-03-2021	Fitting hole is enlarged	12-03-2021	Fitting hole is enlarged
259011	04-03-2021	M3 plug is aborted	12-03-2021	Proposal milling plug away	16-03-2021	Mounting keensert for plug

In case of a fitting hole which can be enlarged, the problem can be easily fixed and it is not needed to do a concession. In case of the M3 plug which is aborted, it is attempted to spark it out. However, it did not work out. Therefore, it was required to do a concession. For the assembly department, which is the customer of this project, it was indeed a problem. A proposal is done for milling away the plug and apply a large thread. In the end, the result of the concession was to mount keensert with the inside diameter of the M3 plug.

For some products, a significant number of products are delivered with deviation, while the number of quality problems can be reduced by adjusting tolerances in the drawing or modifying the model. However, the customer is not willing to agree with modifications/adjustments if it will not lead to lower costs. In these situations, it is often not possible to reduce costs since production of these products is not stable yet. The LS X body, project 7322 324 81038, is such a product which consist of much quality problems. As a result, 80% of project 7322 324 81038 (LS X body) is delivered with deviation.

2.3.3. Dealing with uncertainties

Based on information from the past, it is expected that deviations will occur. However, these expected deviations are not considered in the expected lead time. In case of deviation, additional tasks have to be performed for handling the complaint, which results in longer lead times. Even in the planning, probable required modifications, adjustments and/or additional tasks are not considered. Currently, planning is based on successes, which is not always in line with practice. If modifications and additional tasks are required, these actions have to be performed in between. However, the planning offers little space for Factory Engineering and Programming, which causes difficulties. Moreover, the time that an order is in quarantine results in longer lead times. As a result, the occurrence of deviations results in problems related to late delivery. If failure and/or disruption of the processes occur, the planning is moved by hand.

2.3.4. Price changes

Besides process related uncertainties, prices may contain some uncertainty. In the current situation, it is not known for what price a system is sold at the Parts Manufacturing department. For the Parts Manufacturing department it is a black box what sales has confirmed with the customer. Since it is unknown for what price a system is sold, it is hard to estimate what the target price for purchasing materials or products should be.

Furthermore, prices of materials may change, which results in difficulties for comparing prices. As a result, it is difficult to ensure that the value of the packing slip and the value of the product are in line. If the agreed price and the price on the packing slip are different, the purchasing order comes on the difference list. The difference list indicates that a mistake is made with regard to the price. Based on the difference list, purchasing checks what the mistake is.

The process for purchasing orders which arrives on the difference list is shown in figure 19.

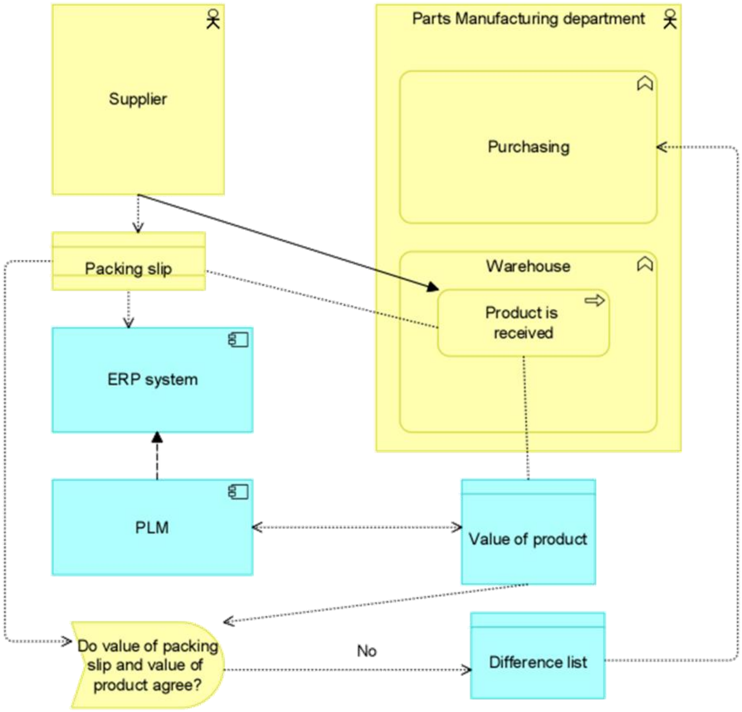

Figure 19. Difference list

2.4. Current ERP system

The current ERP system gives for every order when what manufacturing procedure should be scheduled and what materials are required for that procedure. The current ERP system is an integral planning system, which is in theory reliable. The ERP system is about what have to be made, what the timing is for production and its revision. Moreover, financial processes, information of suppliers, storage of stock and routings are controlled in the ERP system. The current ERP system is BaanIV, which is an ERP system from ’78, is running on Windows 98 and is based on MS Dos. The system is powerful, customized, equipped for adjustments and includes different profiles for different functions such that employees have only competences which are needed for their job. In general, the ERP system is working well, however, it is not user-friendly. The system is organized in a way that users should know exactly what they are searching for. Moreover, the system is cumbersome in such a way that for gathering information needed from the system, many tabs should be opened by clicking. To make it easier to use, many tools are built around it during the years, among others iQbs and tools for doing forecasts.

While external tools are built, the organization is still struggling with the ERP system. The ERP system is not daily used by all employees, but if employees who are not used to the ERP system have to use the ERP system, it is difficult to use and a procedure is needed to make use of it. Moreover, since external tools are used for analysis, data is not directly available. Therefore, in the current situation, it is not possible to follow orders continuously or per hour. Another drawback of using external tools are that multiple files are available, which makes it less insightful.

While machines have capacity limitations, current ERP system calculates with infinite capacity. As a result, the given planning of the ERP system is infeasible. However, in the past, calculating with infinite capacity is chosen consciously, since the company is working with dual source, which means that rescheduling is required by both calculating with infinite and finite capacity. By calculating with infinite capacity it is better visible what bottlenecks are based on what should be done when according to the system. Based on these bottlenecks, the task of the order planner is to decide what will be produced, what will be outsourced and in what sequence parts will be produced. On the other hand, by calculating with finite capacity, a feasible planning is given. However, this planning may include much delay, since such a system could cause that an order is postponed at every process step because of machines which are already full-loaded. In the case of finite capacity, it is sometimes more desired to move an order forward in the schedule.

In the current ERP system, planning is done in buckets, which indicate when manufacturing of products should be scheduled. Dependent on the lead times, orders are planned by the ERP system over weeks. Expected lead times of orders are rounded up, which means that waiting time is included. Moreover, for some products, indications given by the ERP system suggest scheduling production of products for only a couple of hours per week over multiple weeks.

Planning methods used in the current ERP system are Master Production Scheduling (MPS), Material Requirement Planning (MRP) and Project Resource Planning (PRP). Indications for planning manufacturing given by the ERP system are determined by one of these planning methodologies. For MRP and MPS, anonymous indications are given by the ERP system. For MRP, indications are converted into production or purchasing orders and for MPS manual steering is required. Indications for projects, which are determined by using PRP, are not complete. Therefore, revision adjustments are released and discussion is required for projects. In chapter 5, literature research, of this report, these planning methods are described in more detail.

Data used by the ERP system to create indications, such as lead times, should be inserted by hand in the current ERP system. Besides lead times of intern process steps, lead times of outsourcers can be inserted into the ERP system if fixed lead times are agreed with the outsourcer. Currently, fixed lead times are agreed with 12 outsourcers. Moreover, scheduling of production based on the indications given by the ERP system is currently done by hand. At the start of the processes, the availability of required provision is checked by using an exposure profile in the ERP system.

Besides data required for giving indications for planning manufacturing, information about molds and clamping jigs are registered in the ERP system. However, these tools cannot be linked to specific process steps in current ERP system. Moreover, the ERP system is not equipped for reporting the availability of molds and lifting equipment.

Other limitations of the current ERP system are lacking overviews of the engineering part of projects and feedback options. The current ERP system is only used for controlling production of orders. Controlling and planning the proto phase and work preparation tasks of projects are not done in the ERP system. In the current ERP system, the preparation trajectory is not visible and planning of FE and programming is not available in the ERP system. Due to the lack of feedback options in the current ERP system, production cannot give feedback directly, since the status of production steps of orders can only be in process, cancelled or finished. Intermediate progress of production steps cannot be given by the current ERP system.

Moreover, current ERP system lacks options for reporting machine failures, disruption, maintenance and quality deviation. In the current ERP system, putting orders/products in quarantine is not possible. Moreover, the current ERP system is not equipped for reporting when maintenance is required. To manage maintenance, technical services uses its own system. In the current ERP system, products with quality deviation are mutated and the status of the last performed operation of the order is not updated. Moreover, products with deviation are thrown away in the current ERP system.

2.4.1. Connected systems

When a new project arrives, Factory Engineers create the routing of the production process into the ERP system and prepare documentation, which is imported into Siemens Teamcenter. In both the ERP system and Teamcenter, tools are reported, such that data can be uploaded. In Teamcenter, databases, control programs and tools are awarded to process steps. Tools created in Teamcenter are connected by the documentation for manufacturing. Teamcenter consist data of proceedings and what materials are required.

Teamcenter is one of the inputs of Soflex. Soflex is a robot control system, which checks when processes have to be done and if everything is available. Soflex extracts data from the ERP system, this data is extracted in one dump when a production order is received. However, if something changes is the current ERP system, it will not be changed in Soflex. The output of Soflex are operating durations and the status of operations. Furthermore, Soflex shows the planning of parts which have to be finished before the end of the week, such that machines can be optimally utilized.

Another system to which the ERP system is connected is Product Lifecycle Management (PLM). PLM includes product specifications and documentation for the manufacturing of parts. In PLM, information of anonymous orders are reported, which include price information. Prices for different batch sizes can be found in staffels under the product name. Currently, PLM is the generic system and production orders are linked to PLM. However, a Manufacturing Execution System (MES) can be used to digitalize production information to check what skills are required for the proceedings which are in PLM. MES is a serving hatch for production, includes an overview of skills which are required for performing specific proceedings and can be used to digitalize production information. In the current situation, MES is not used.

Proceedings for which skills are required have to be performed by employees which are certified for that skills. In HR systems, skills of employees are reported. Employees should be scheduled to processes for which they are certified for the required skills. Skills are divided in operating machine skills and product specific skills. If an employee is certified for operating a machine, that certification is unlimited valid, while product specific skills ends when an employee has not produced that specific product for a while. Controlling the worked hours is currently done by clocking hours in Orgatime, which is a system for working hours.

Another system which is connected to the ERP system is portal sharepoint environment, which is a purchase portal. In this portal, outsourcing and purchasing orders are confirmed by suppliers/subcontractors. Information from the ERP system is printed to the portal and submitted for approval to managers. Till €250000 approval of the manager of the Parts Manufacturing department is required and above that amount approval of the overall manager of VDL ETG Almelo is required.

Last, data of the ERP system is connected to iQbs. Data is retrieved from the ERP system and used for analyzing and reporting in iQbs. IQbs is an Excel interface, which makes use of pivot tables. IQbs is used for among others overviews of machine loading, analysis of KPIs, analysis of orders, overviews of worklist and overviews of CLIP information. The drawback of iQbs is that printing iQbs is very complex and has a long duration. Therefore, iQbs are only printed during night, which results in the fact that data is only updated once a day and is lagging one day behind.

2.4.2. Other systems

Another system used at the Parts Manufacturing department is the Warehouse Management System, in which stock is registered. In the past, stock was registered in the ERP system, but nowadays stock of most products is registered in the Warehouse Management System (WMS).

However, in the current situation, not all products are clear transferred from the ERP system to the WMS.

2.5. Conclusions context analysis

To conclude, in this chapter a context analysis is given with a description about the Parts Manufacturing department, processes at the department and the current ERP system.

At the Parts Manufacturing department of VDL ETG Almelo new customer orders arrive continuously and limited machine capacity is available intern. To deal with limited machine capacity, the department makes use of dual source, which means that customer orders are produced intern and/or purchased. When a new customer order arrives, the order is always accepted and an investigation is done what will be performed intern, what process steps will be outsourced and what orders will be purchased based on the complexity of production and required technologies.

Processes at VDL ETG Almelo are long, complex and diverse, includes a variety of uncertainties and engineering tasks for projects is experienced as difficult. Planning work preparation tasks of an order is dependent on among others, the maturity of manufacturing process design of the product, available capacity at FE and programming and expected lead time of a product of the order. Engineering tasks for projects include decision-making about the process routing, costs, quality requirements and materials, preparing documentation, preparing measuring reports, making procedures for production and programming programs. Based on data and experiences from the past, it is expected that the processes include unpredictable events and modifications due to uncertainties, however, in the current situation, uncertainties are not anticipated in the planning.

The department strives to high performance of the processes, in which high performance of quality and logistics are the most important focus points. Important KPIs which belongs to these focus points are high quality performance and delivery reliability.

Quality is controlled by QE, which checks if documentation meets customer requirements, controls complaints and manages a recovery strategy when quality deviation is observed. Order flows are controlled by Logistics, which is responsible for planning orders, ordering materials on time and controlling production orders.

The current ERP system is BaanIV, which is powerful, customized and equipped for adjustments. However, it is not user-friendly, cumbersome in use, lacks feedback options and is not insightful. To make it easier to use and to create analysis options, external tools are used.

Chapter 3. Shortcomings, bottlenecks and problems

In this chapter, we intend to clarify the drawbacks and shortcomings of the current ERP system and the current organization of processes. Moreover, we intend to clarify reasons for late delivery. Drawbacks, shortcomings and problems described in this chapter are gathered by interviewing stakeholders, contain problems where stakeholders are facing with and its root-cause relationships.

First, problems experienced at the Parts Manufacturing department of VDL ETG Almelo are divided in ERP system related drawbacks and process related drawbacks. Moreover, for both ERP system related drawbacks and process related drawbacks, project related, logistics related and quality related shortcomings are highlighted.

3.1. ERP system related drawbacks

BaanIV, the current ERP system, is cumbersome in use and difficult to use for not-regular users. Moreover, the system lacks a visual tool to show clearly what is going on in the process. Consequently, it is not insightful if processes of orders are on track. Communication between production steps lacks, since interaction and feedback options are not included in the current ERP system. Since overviews of the processes are not visible in the ERP system, iQbs is used to control processes. However, data in iQbs is running behind, since dumps of the ERP system are only updated during night. Since controlling lists are running behind and the ERP system lacks feedback options, anticipating on the progress is done too late.

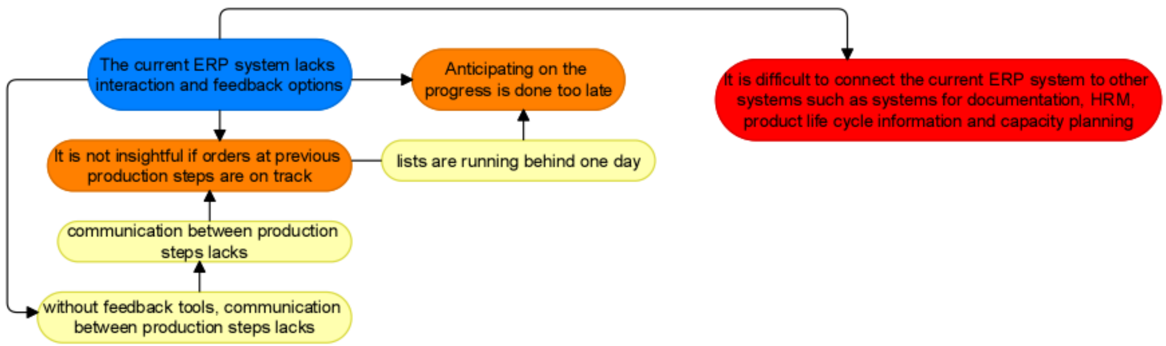

Figure 20. Lacking interaction and feedback options

Besides controlling processes in iQbs, iQbs is used for analyzing data, since the ERP system is not furnished with analyzing functions. In the current situation, multiple steps are required to be able to analyze data from the ERP system, which is cumbersome.

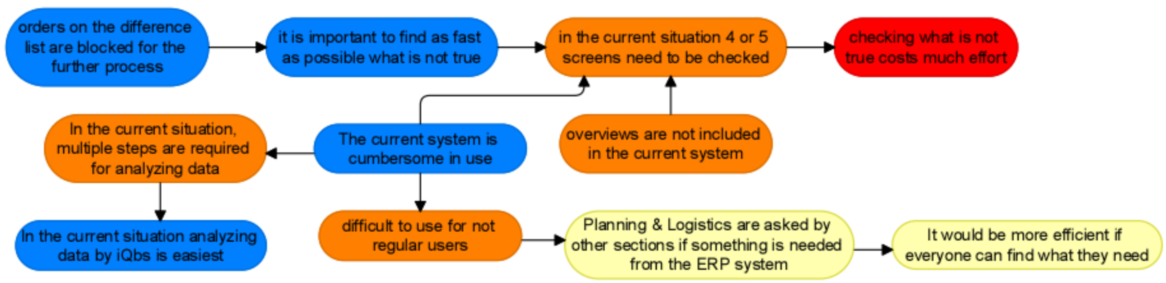

Figure 21. ERP system is cumbersome in use

Furthermore, in the current ERP system, process steps can be reported as finished without the requirement that earlier process steps have to be reported as finished. As a result, it is possible that another task is reported as finished and process steps may be skipped, which may cause quality problems.

Other issues related to the ERP system are outsourcing/purchasing related, maintenance related, stock related and related to connect ability. Outsourcing and purchasing related issues include the absence of taking capacity limitations, agreements for minimum outsourcing and minimum batch sizes into account. The current ERP system divides purchasing/outsourcing orders over suppliers, while minimum batch sizes may not be met. Moreover, the ERP system does not consider capacity limitations of outsourcers and agreements made for minimum outsourcing.

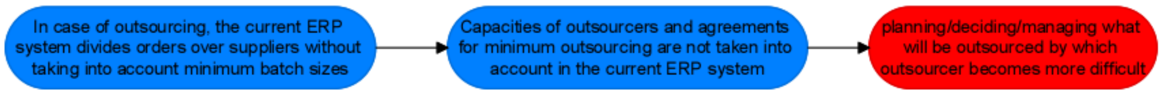

Figure 22. outsourcing orders

The current ERP system does not include a tool for planning maintenance and bites and carts are not reported into the ERP system. Since bites and carts are not reported, information about the availability and costs of bites and carts are not available. As a result, delay can be caused if bites or carts are not available or lost. Furthermore, difficulties are experienced with connecting current ERP system to other systems, such as systems for documentation, human resource information, product life cycle information and capacity planning.

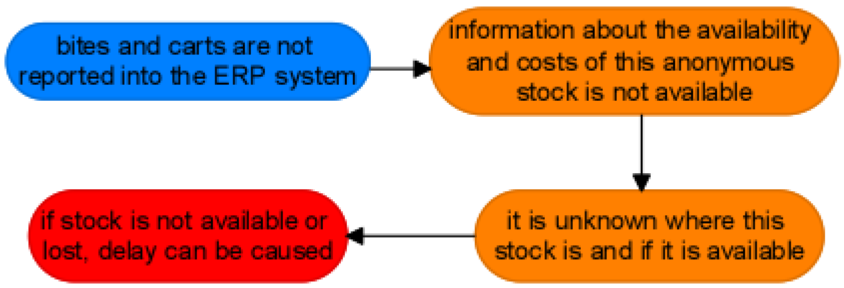

Figure 23. Lacking tool management

3.1.1. Project related shortcomings of the ERP system

Furthermore, the ERP system has project related shortcomings. The ERP system does not distinguish new project from flow product orders, while these orders follow a different process. Especially work preparation tasks are different for projects than for flow products. Engineering tasks of projects are not visible in the ERP system, which results in a lack of insight for FE, programming and purchasing. The ERP system does not indicate when materials should be ordered, when processes should be continued and what deadlines for FE, programming and purchasing are.

3.1.2. Logistics related shortcomings of the ERP system

While engineering tasks are not visible in the current ERP system, production processes are also not insightful in the current ERP system. In the current ERP system, production orders are only reported if a production step is completely finished for all products of the order. If part of the production order is not finished or in quarantine, the whole order is not reported as complete. As a result, many production orders remain open and it becomes unclear what order requires proceedings first.

Since process steps are only reported as finished if production steps are completely finished for the whole order, the current ERP system gives a distorted overview and intermediate progress is not reported. In this way, it is not visible if orders are on schedule and the given backlog by the ERP system is bigger than the actual backlog. For example if an order is at 80%, it is still reported as 0%.

Moreover, misclips give a distorted overview as well, since the current ERP system reports all orders which are split or not include the complete amount as a misclip. Therefore, too much orders are reported as missed in the current ERP system, while due dates of split orders may still be met. Orders may split in case of both quality and logistical issues. However, splitting orders in the current ERP system have to be done by hand, which is cumbersome. Moreover, in the current ERP system customer orders cannot be confirmed and split.

Another logistic related shortcoming of the ERP system is that the ERP system is cumbersome and time consuming in use. Data have to be inserted by hand in the ERP system, planning in the ERP system is time consuming and searching into the ERP system is cumbersome. For not regular users, the ERP system is difficult to use, which causes that Planning & Logistics is often requested for help if something is needed from the ERP system.

Planning indications given by the ERP system have to be rescheduled, since the ERP system calculates with infinite capacity and no trigger is given when the maximum capacity is reached. Moreover, detailed planning is required at the Parts Manufacturing department, while planning indications given by the ERP system are given in big buckets which lacks precision. For some products, indications indicate to only produce for a couple of weeks, which is not optimal for the flow of manufacturing processes. With the number of ongoing orders, it is very time-consuming and not realistic to reschedule and insert the planning by hand in the ERP system, while inserting by hand is required in the current ERP system since the ERP system does not recognize all characters. If given planning indications changes, adjustments have to be done by hand in the current ERP system. As a result of planning by hand, imbalance in the planning and production is caused, since too much or too many is scheduled.

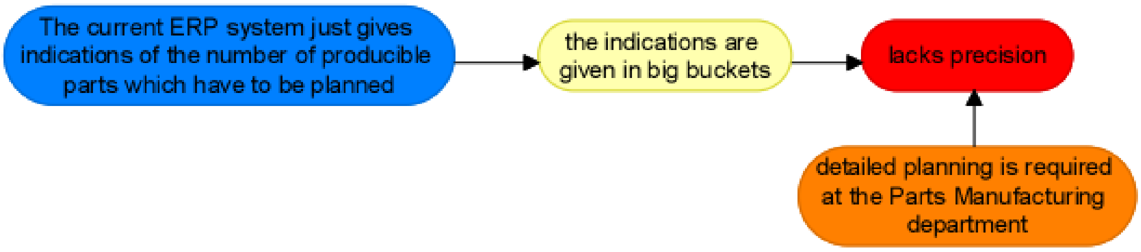

Figure 24. lacking precision of indications

Another drawback for the logistic processes is that processes are blocked in current ERP system if the value of a product is not in line with the value of the packing list. If these values differ from each other, the order is placed on a difference list. Since processes are blocked when the order is placed on a difference list, it is important that the differences are find as fast as possible. However, in the current ERP system, it costs much effort to find out which costs are correct, since overviews are not included in current ERP system and around 4 or 5 screens need to be checked to compare data.

3.1.3. Quality related shortcomings of the ERP system

Besides processes which are not visible in the current ERP system, it is not visual which deviations and problems are occurred during production. Since it is not visual what deviations and problems occur during production, it is not clear what these problems are, why these problems occur and what adjustments are needed. As a result, having discussions at the work floor about problems which have occurred and how these problems should be solved is difficult. Moreover, the ERP system is not insightful in dealing with disapproval. In the ERP system, it is not clear how to deal with disapproved products.

Another quality related shortcoming of the ERP system is that orders cannot be put in quarantine in the ERP system. In the current situation, products which include some deviation are indicated with "1" in the ERP system and exported into a Q-list in iQbs. As a result, the Q-list is very long and includes both orders which require actions and orders which are waiting for a decision from the customer. As a result, it is not insightful which orders require actions and for which orders actions are already taken. Moreover, controlling/managing the Q-list is difficult, since it is not insightful what orders require actions and in which sequence.

3.2. Process related drawbacks

Besides ERP system related drawbacks, process related drawbacks are experienced at the department. The long chain at the company is experienced as a bottleneck, since the long chain is not insightful. As a result, operators have only responsibility for their own tasks instead of for the whole process. The ERP system of the Parts Manufacturing department is connected to the ERP system of the Assembly department and Sales, since the chain is dependent on the demand side. However, the Parts Manufacturing department and the Assembly department are not aligned, which causes much disturbance. In the current situation, dealing with the long chain and modifications in the chain are bottlenecks, since the demand side has impact on the whole chain. New customer orders have much impact on the whole process and causes orders becoming in backlog.

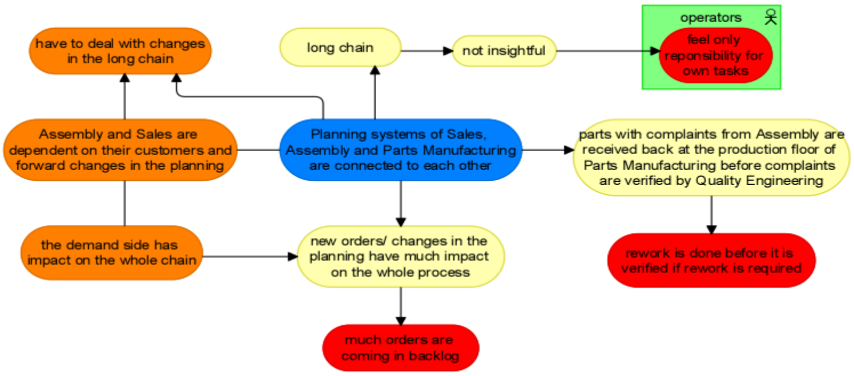

Figure 25. Long chain

In the current situation, orders ordered by the Assembly department are given in big buckets, while only 1 product per week is required. If these orders are delivered separately to the Assembly department and part of the order is coming later than the demanded delivery date, the status of the order in the ERP system indicates that the order is in backlog. However, the order may be not delivered too late since delivery was not necessary yet. The problem of having big buckets in the demand is that manufacturing takes longer and other orders are waiting. However, the bottleneck is that the Assembly department is not intending to change demanded buckets.

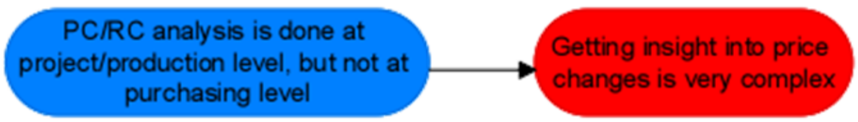

Figure 26. Insight into price changes

Other process related drawbacks are procedures for measuring performances which are not accurate or complete. Among others, Pre-calculation/Re-calculation analyses are not performed at purchasing level, while it is performed at production level. Since PC/RC analyses are not done at purchasing level, acquiring insight into price changes is difficult. Procedures which are not accurate are the procedure for counting the number of operating hours and the procedure for forecasting capacity. Operating hours are counted by clocking of operators, while operators have both operating and non-operating tasks and part of the production is done unmanned. Forecasted capacity is determined based on the capacity of the last 8 weeks, while the actual capacity is dependent on the number of operators scheduled. Furthermore, only machine capacity is considered during planning, while processes requires also man hours. Especially, during work preparation, required capacities are required man hours.

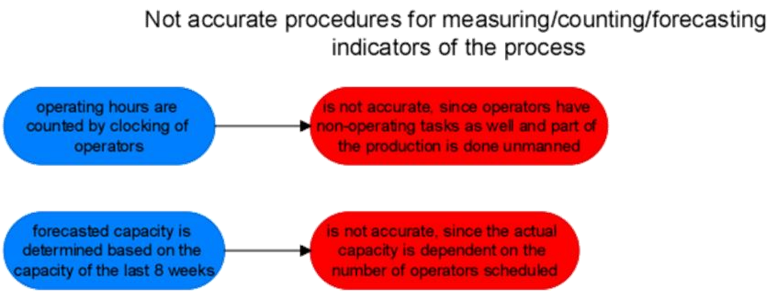

Figure 27. Not accurate procedures for measuring indicators

Moreover, process related drawbacks include project related, logistics related and quality related shortcomings as well.

3.2.1. Project related shortcomings of the process

The main project related shortcoming of the process is that the company is not equipped for projects. Since the company lacks some project management and many projects are manufactured at the company, projects are a bottleneck of the process. New projects are difficult to manage, since preparation tasks are required before production can start and the due date have to be met. Moreover, for new projects, it is not known beforehand, what tools are required and when.

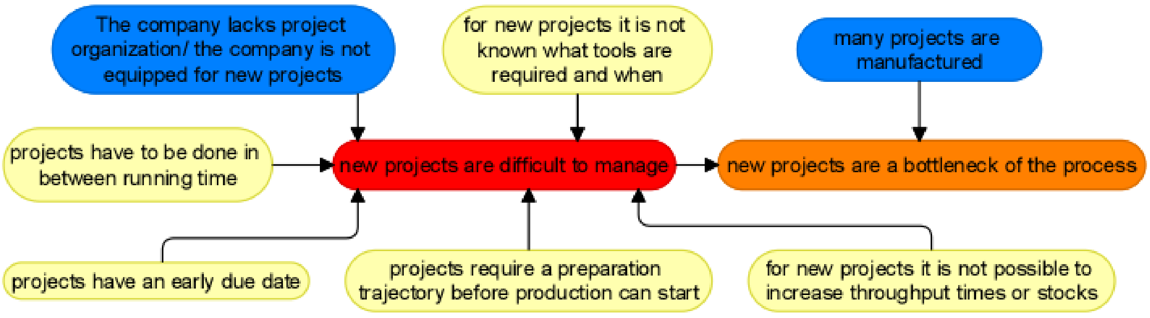

Figure 28. Difficulties of managing projects

Furthermore, preparation tasks are not visible in the ERP system. Moreover, booked hours by programming and the progress of programming are not visible for production. Therefore, it is difficult to control work preparation tasks. Planning of work preparation tasks of FE is currently managed in Excel in separate files. Since separate files are used, it is more likely that deadlines may be overlooked.

3.2.2. Logistics related shortcomings of the process

Lack of planning work preparation tasks has impact on further processes. Production processes, for which preparation tasks have to be completed, cannot start earlier than work preparation tasks are finished. Since the planning of work preparation tasks and planning of production are currently not completely in line with each other, production may be scheduled, while production steps are not released yet. As a result, production time is lost and scheduled machine capacities are not utilized.

Currently, anticipating on the progress of orders is done late, since planning is based on data of one day behind and the current ERP system lacks feedback options. Data of the ERP system is extracted during night into Excel. Overviews given in Excel, which are lagging one day behind, are used to plan and control processes. Data which is lagging one day behind is lacking last minute factors, such as materials which are not supplied on time, interruptions and illness. To deal with last minute factors, some modifications are updated by hand every 15 minutes based on feedback of suppliers and notifications about disturbances. However, overviews and the planning are not completely updated. Moreover, rescheduling is done by hand in the current situation, which results in irregular planning. As a result, imbalance of production is caused and production balances the number of orders by themselves, which results in variation of delivery speed including outliers and fluctuating stock levels.

Figure 29. Splitted orders and orders which remain open in the ERP system

Moreover, in the current situation, the planning is not always insightful, which may cause that operators choose production orders by themselves to perform production steps. As a result, other orders may be performed than planned. Imbalance of production and delay are results for proceeding other orders than planned. To deal with imbalance of production, production is leveled. However, leveling production is time-consuming and request much effort from planning & logistics.

3.2.3. Quality related shortcomings of the process

Besides preparation tasks which are not visible in the ERP system, concession processes are not visible in the current ERP system. In the current situation, deviations and uncertainties are not considered in the planning. If deviations occur, concessions have to be done, which may take long, and products have to start up again. When products are in quarantine, the order is blocked for the further process, before it is started up again. Therefore, deviations cause often extensions of lead times of processes.

Moreover, quality specifications are high, which results that products are coming often in quarantine and concessions need to be requested, which costs much time and effort. As a result, much delay is caused. For some products, high quality specifications results that orders of that product are coming practically every time in quarantine.

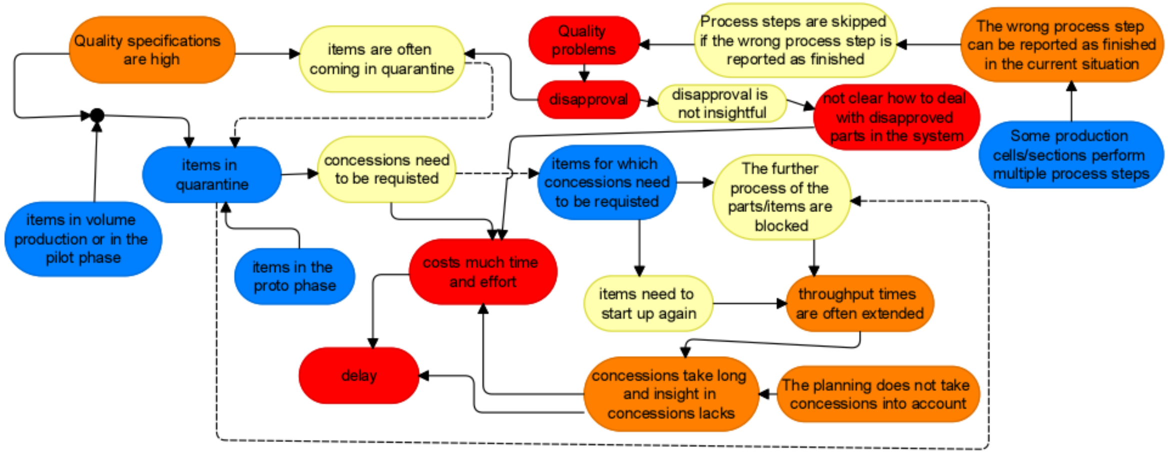

Figure 30. Quality deviations

Furthermore, not aligned processes of the Assembly department with the Parts Manufacturing department causes quality related issues. In the current situation, the Assembly department returns both the product and the complaint when a problem has occurred. However, since the Assembly department returns the product and the complaint simultaneously, the product is first received at production before the complaint is verified by Quality Engineering. As a result, in the current situation, rework may be done, while it is not verified if rework is required.

3.3. Late delivery

Delay of processes are caused by a variety of causes. Causes for late delivery are related to failures & deviations, price differences, materials which are not available or on time, other proceedings performed than planned and changes on the demand side.

In case of failures and deviations, processes are interrupted due to machine failure or quality deviations. Machine failure needs to be fixed before the machine can be utilized, which indicates that processes are interrupted or rescheduled to other machines. Orders from which products have quality deviations are put in quarantine, requires some rework or concessions have to be requested for orders with quality deviation. Products in quarantine may have a long waiting time and concessions may take long. Moreover, processes of products in quarantine have to start up again. These actions may have a long duration and may cause delay.

In case of price differences, processes may be interrupted, since processes are blocked if the value of the packing list is not in line with the value of the material. In that situation, the correct values have to be found before processes are continued. This interruption may cause delay.

Moreover, materials which are not available or late may interrupt the process, since production cannot start if required materials are not available. These materials may include both materials for products and tools. Tools may be in use for other processes and delivery of materials for products may be delayed.

Moreover, the Assembly department and customers may have influences on the planning, and may cause delay, by placing new orders or modifying demand. If the Assembly department or another customer changes demanded deliveries, backlog may be caused, which may have influence on delivery of the corresponding order and other orders. Besides changes in demanded deliveries, new orders may have influence on the planning of other processes.

Furthermore, performing other orders than planned may cause deviation in completion of production. Products which are scheduled to be produced, but are not produced since another order is performed, may be delivered late, since delay may be occurred.

3.4. Conclusions problem analysis

To conclude, in this chapter drawbacks of the ERP system and intern processes experienced at the department are described.

The current ERP system is cumbersome in use, lacks a visual tool to get insight into processes and lacks feedback options. Working with the ERP system is time-consuming, insight into problems cannot be acquired by the ERP system and intermediate progress is not visible. Moreover, connect ability problems are experienced for the current ERP system with other systems.

Controlling processes is difficult in the ERP system. Therefore, controlling the processes is done in iQbs. However, in iQbs, data extracted from the ERP system is only updated during night, which means that controlling the processes is done by anticipating based on data that is lagging 1 day behind.

Moreover, difficulties with managing projects and quality issues are experienced. Engineering tasks of projects and products in quarantine are not insightful in the current ERP system. Furthermore, for products in quarantine it is not insightful if actions are required or if it is required to wait on a decision of the customer. Moreover, products are coming in quarantine often since quality specifications are high.

Drawbacks regarding intern processes include misalignment between departments, which causes much disturbance and imbalance of production due to performing other orders than scheduled. Disturbance and imbalance of production may cause interruption and delay. Other causes for interruption and delay are among others machine failure, materials which are late or not available and processes which are blocked due to price differences.

Chapter 4. Needs and desires

As mentioned in previous chapter, processes are currently not insightful and clear overviews are lacking in the current ERP system. Meanwhile, having clear overviews is one of the most prominent desires and needs of the department according to the interviewed stakeholders. Other prominent desires and needs of the department are related to analysis options, an insightful and user-friendly (easy to use) ERP system, getting insights in processes, an ERP system which can be connected to other systems and an ERP system which is equipped for automation. In this chapter, desires and needs for the department are described.

The most important need of a new ERP system is that it should support the processes. It is important that planning methodologies such as MRP are implemented for giving indications of production orders. Moreover, it is desired that the ERP system is easy to use, functional and gives insight/overviews of the processes. Clear overviews are desired for among others controlling logistical processes, projects and quality issues and analyzing the performance of the department. It is desired that the system is equipped for planning and analysis purposes without a need for extern tools.

Besides overviews for controlling logistical processes, projects and quality issues and analyzing the performance of the department, overviews with general information about the demanded product and its processes and overviews with regard to outsourcing and purchasing are desired.

It is desired to have overviews of demanded products, its process routings, required production steps and its quality requirements. Moreover, it is desired to have insight into Bill Of Materials and who is working on what order/production step. Furthermore, it is desired to have a clear overview of the planning including assigned machines and required tools for performing production steps. For required tools it is desired to have overviews about the availability of these tools. Moreover, it would be beneficial to have insight when maintenance or verification is needed for tools and when which measuring program is needed.

It is desired to have a functionality for tool management in the new ERP system to have insight in available tools, utilized tools, when tools are verified and when tools require maintenance. It is desired that the tool management functionality gives a trigger when a tool is needed, when tools require maintenance and when tools are running out. For measuring materials and tools, it would be useful if supplying lists can be generated automatically in the ERP system.

For outsourcing and purchasing orders, it is desired to have overviews of orders which are at the supplier, when outsourcing/purchasing orders should be returned and expectations of arrival of outsourcing/purchasing orders for suppliers. Overviews of percentages of outsourcing/purchasing orders assigned to suppliers and the minimum percentage agreed for production at these suppliers are desired. Moreover, it is desired to have some insight into price changes based on PC/RC analyses.

Besides overviews of the percentages of outsourcing/purchasing orders, it is desired to have a functionality which considers these percentages and gives a trigger if the minimum percentage agreed is not met. Moreover, it is desired that the new ERP system is equipped for considering optimal batch sizes when outsourcing/purchasing orders are divided over suppliers, since batch sizes may have impact on ordering prices. Moreover, it is desired to agree contract prices and fixed lead times with all suppliers, such that lower prices can be agreed and less uncertainty is available in the planning. For orders at suppliers with whom fixed lead times are not agreed, it is desired that supply dates are confirmed. Furthermore, a functionality for forecasting orders including its deviation for one year forward is desired. It would be useful to have overviews of forecasted orders, from which expectations for suppliers can be extracted and insight into expected tasks per section for these orders can be acquired.

Moreover, for intern production, overviews for the workfloor are desired, such that operators have insight in their own planning, operating hours and who performs what proceeding. By having overviews for the workfloor, the workfloor can anticipate on the situation by themselves, which may have impact on the responsibility and influence on the output of the workfloor.

Therefore, a functionality for visual overviews for production is desired. It is desired that these overviews are available per production cell. Moreover, a functionality for counting operating hours is desired.

For planning, it is desired that planning of the Assembly department is detached from the planning of the Parts Manufacturing department. It would be beneficial if new customer orders are first send as a request which have to be confirmed such that the order may be split in multiple production orders and delivery dates can be agreed based on the influence of the new order on the planning and when capacity is available for production.

Moreover, for simplicity of planning, it is desired that the new ERP system includes simulation options and/or a functionality for easily selecting orders for creating a planning. Furthermore, for making the processes more lean, eliminating waiting times and a detailed planning is desired. For a more detailed planning, scheduling is required. Therefore, it is desired that the (ERP) system is able to deal with scheduling problems. It is desired that intern production is capable to deal with fluctuating demand and that capacity restrictions and uncertainties are considered during scheduling for a transparent planning. To deal with changes and uncertainties, it is desired that the planning system is equipped for dynamic planning.

4.1. Project related desires

Since projects contain in general much uncertainties, it is beneficial to have clear overviews of projects to minimize these uncertainties. For projects, it is desired to have an overview of the whole process including the preparation trajectory. In that way, the overarching picture of the whole project becomes more visible, which results in a clear overview of how the processes are performing. It is desired to register projects in one system, such that more insight can be get. It is desired to introduce project planning, such that deadlines and deliverables are more clear and costs of engineering tasks can be evaluated better.

A functionality for project management is desired in the new ERP system to control the whole process including work preparation tasks. It is desired to have an ERP system with a good infrastructure for planning tasks of FE, QE and Programming, such that engineering tasks can be made more plannable and hours and costs of the engineering can be justified better. A more project focused system is desired, such that engineering tasks can be better integrated with the production process and deadlines for deliverables of FE and programming are better visible.

For projects it is desired to have overviews of preparation tasks and the duration and progress of these tasks. It is desired that overviews of preparation tasks include all actions which have to be performed in work preparation tasks for new projects and required adjustments for existing projects. Moreover, it is desired to have insight in capacities, workload and required durations of tasks of QE, FE and Programming, such that it can be justified if more time and/or more colleagues are required. Furthermore, it is desired to have insight in the progress of work preparation tasks and in the booked hours of Programming & FE. Moreover, it is desired to have overviews of tasks and projects per person at Programming and FE to control projects.

During work preparation tasks, it would be beneficial to schedule intermediate checks, in which documentation is checked, to control quality. It is desired to have an useful and easy functionality to create routings and include preparation tasks and quality checks in the routing in the ERP system. It would be beneficial if inserting by hand is not required for creating routings. Furthermore, it is desired to have a functionality for checking and approving documentation and a functionality for sending and forwarding documentation, such as 3D models and settings. Moreover, it is desired to have insight in the pgp phase of a product, which indicates if a product is a new project, existing project or flow product, by a notification in the ERP system.

4.2. Logistics related desires

For a clear visual overview of the progress of previous production steps and for controlling processes, a planning integral/tracking document with feedback of previous production steps is desired. It is desired to update intermediate progress, such that the progress of orders is more visible in case of long durations for proceedings.

For logistics, it is desired to have overviews of the progress of processes, machine loading and capacities. It is desired to have insight into orders which are in progress, the status of orders, the corresponding due dates of the process steps of orders, confirmations and feedback of previous production steps and priorities. It is interesting to have insight in which orders are released and which orders are in backlog. It is desired to have insight into machine loading and capacities of resources to manage resources and to create more flexibilities in planning. Moreover, for orders which have delay, it is desired to have insight in costs and reasons for delay. Furthermore, it is interesting to know which products are included in the order and if delay is structural for these products.

Moreover, it is desired to measure misclips in a more accurate way in the new ERP system. It is desired that misclips are measured based on inventory levels and not based on split orders. Furthermore, it is desired that reporting process steps are blocked until previous production steps are reported as finished.

4.3. Quality related desires

In case of misclips due to quality problems, it is interesting to have insight in the reason quality problems have occurred, the consequences of the quality problems and the duration of dealing with quality problems. It is desired that products which have a quality issue are detached from the rest of the order, such that the process of other products of the order can be continued without staying on production lists. Moreover, it is desired to have an overview of products which are in quarantine, for how long these products are in quarantine, where the problem has occurred in the production process and how can be dealt with the quality deviation.

It is desired that the new ERP system is equipped for dealing with quality issues. A functionality for putting products with quality deviation into quarantine is desired in a new ERP system. Moreover, it is desired that production cells at which quality problems occur can be indicated by the ERP system and that the ERP system includes a button or setting to indicate that delay will be probably occurred due to quality disruption. It is desired that both operators and the heads production are able to put products into quarantine in the ERP system and that products in quarantine are visible by a malfunction notification.

Products for which a decision have to be made for granting the quality deviation, accepting a recovery strategy or scrapping the product with quality deviation, a concession is requested to the customer. It is desired to have insight into requested concessions and when actions have to be succeeded for concessions.

For products in quarantine including products for which concession is requested, it is desired to have a monitoring functionality in the ERP system for controlling products in quarantine and for controlling the concession process. It is desired to monitor products in quarantine and the process of concessions to have better overviews for making decisions. Moreover, it is desired that clear deadlines are defined for products in quarantine. Furthermore, it is desired that the quarantine list is split into 2 lists, namely a list with orders for which actions have to be done and a list with orders which are waiting for a decision of the customer after a concession request is send.

Moreover, it is desired to have insight in these quality problems and complaints to check what problems are doubtful. Doubtful problems are problems which occur regular for the same product and/or at the same production step. Therefore, it is desired to have insight in products and production steps where problems occur. By having insight into quality problems, corresponding products, and production steps, quality issues can be better controlled and managed.

Furthermore, it is desired to have insight in delay caused by quality deviation and other interruptions. Besides delay due to interruption of quality deviation, quality deviation may cause costs of non-quality. Therefore, having insight into percentages, numbers of products with quality deviations and costs of quality deviations/non-quality per product and per production cell is desired.

Besides having insight into delay due to interruption and costs of non-quality, it is desired to measure the performance of delivery reliability for products with quality issues, such that KPIs for the performance of delivery reliability can be controlled better.

Moreover, it would be beneficial that processes of the Assembly department are detached from processes of the Parts Manufacturing department for quality issues at the Assembly department, which orders are send back to the Parts Manufacturing department, such that complaints and documentation can be verified first before products are received back at production. It is desired to have insight in information about approval of documentation, such that production processes can be blocked if documentation is not approved yet. Besides checking and approving quality documents, it is desired to archive quality documents for analysis purposes.

4.4. Desires and needs for analysis options

Besides archiving quality documents for analysis purposes, it is desired to retrieve data fast from the ERP system and that information is easily accessible, such that performances of KPIs can be analyzed. It is desired to have clear overviews of performances of KPIs including pre- and recalculations, performances of production cells and sections and the yield per product and production cell. A standard dashboard or report with overviews of performances and achievements is desired.

It is desired to have a supporting ERP system for making decisions, which includes functionalities such as analysis options, visual tools and simulation tools. Simulations are desired for getting insight in consequences of modifications in processes and/or planning. By using simulations before making decisions, mistakes can be eliminated. Simulations can be done for among others lead times, waiting times and no hard processing times. Moreover, it is desired to analyze processes and problems, by analysis methods such as FMEA, including analyzing the corresponding products, materials used, the process routing followed and machines utilized.

4.5. Desires and needs for automation, digitalization and connect ability

Besides for controlling processes and analyzing purposes, having clear overviews of demanded products, process routings, required production steps and quality requirements may be beneficial for transforming into a digital company. By having clear overviews, information can be forwarded easier.

To use data from other systems and being equipped for automation, traceability and having access to more up-to-date data, it is desired that the new ERP system can be connected to other systems such as PLM, MES, Soflex, HR systems, WMS, dual source, Teamcenter, tool management systems and portals of suppliers for purchasing and/or outsourcing. By connecting multiple systems, it is easier forward/send information and more direct contact and better communication between production steps can be achieved.

It is desired that the ERP system is equipped to read Soflex and to give feedback to Soflex, such that modifications can be taken over automatically. Moreover, a connection with sales is desired since it would be beneficial to have insight into the price of the sold system or at least into a target price for the sold system.

Information and documents which are desired to forward are among others documentation, delivery reports, feedback, settings, required tools, information about quality issues, changes in the planning and approval requests. Documentation which is desired to forward is technical documentation including 3D models and drawings. Feedback includes updates from production cells and other sections about the progress of engineering tasks and about previous production steps. These updates include confirmations of delivery dates. Regarding quality issues, information about products with quality deviation and the corresponding quarantine and concession processes are desired to forward.

Furthermore, digitization is desired for maintaining and controlling production folders. In a digital environment, multiple folders can be selected and adjusted simultaneously. In a digital environment, adjustments can be done for all, multiple or separate folders at the same time.

4.6. Conclusions needs and desires

To conclude, needs and desires for a new ERP system are drawn in this chapter. It is desired to have an insightful and user-friendly ERP system, which is functional, easy to use and supports processes of the Parts Manufacturing department of VDL ETG Almelo. Another prominent desired desire is having clear overviews of processes, projects including engineering tasks, general information of products, processes and requirements, products in quarantine and information about outsourcing and purchasing orders. These overviews are desired for analyzing performances of the department and for controlling processes, projects and quality issues.

For overviews of projects, it is desired to have insight in engineering tasks, the required duration and progress of these tasks, deadlines, deliverables, the maturity of the manufacturing design process of the project, costs, capacities and workload. It is desired that the new ERP system is a project focused system with a good infrastructure for planning FE, QE and Programming projects tasks.

For controlling processes, it is desired to have overviews of the progress of processes, the planning, operating hours, machine loading and capacities. For having a more up-to-date overview of the progress of processes, updating intermediate progress and feedback options are desired.

It is desired that a schedule can be generated in the new ERP system, which can deal with fluctuating demand, capacity restrictions and uncertainties. Moreover, it is desired that new customer orders can be confirmed or modified in consultation with the customer, such that big fluctuations can be prevented.

For controlling quality issues, it is desired to have insight in reasons for quality problems, consequences of quality problems, the expected duration of dealing with the quality problems, products in quarantine and concessions. It is desired that the ERP system includes a functionality for putting products in quarantine and that products in quarantine are visible by a malfunction notification. It is desired to have a monitoring functionality for controlling products in quarantine and for which concessions are requested.

It is desired to get insight into doubtful quality problems, in predictable delay, in costs of non-quality and into the performance of delivery reliability for products with quality issues.

For analysis purposes, it is desired that the ERP system is equipped with analysis options, visual tools, simulation options, a functionality for forecasting orders and having overviews of forecasted orders, that the ERP system is equipped for retrieving data fast and that information is easily accessible. A standard dashboard or report is desired for overviews of performances of KPIs. It is desired that orders can be easily selected in the ERP system for planning, analysis and controlling purposes.

For maintaining, controlling and updating production folders, it would be beneficial if production folders can be easily selected and that production folders are digitalized. Moreover, digitization is beneficial for automation and connect ability with other systems. It is desired that the ERP system is equipped for automation for better traceability of orders and for having access to more up to date data. It is desired that the ERP system can connect with other systems, such that communication between production steps, sections and systems can be improved.

To summarize, functionalities for controlling processes, analyzing performances, dealing with capacity restrictions and uncertainties, project management and managing quality issues are desired by the department. To investigate what is suggested in literature for dealing with capacity restrictions and uncertainties, for managing projects and for controlling and analyzing processes, literature research is done in capacity planning, dynamic scheduling, project planning, project management and control systems. Findings of literature research are described in chapter 5. Subsequently, some findings found in literature are used for designing a linear model for scheduling and decision making which considers capacity restrictions in chapter 6. Moreover, the linear model designed in chapter 6 intends to be supportive for managing projects and dealing with uncertainties.

Chapter 5. Literature Review

As mentioned in previous chapter, project management and dealing with capacity restrictions and uncertainties during scheduling are desired subjects at the Parts Manufacturing department. To investigate how can be dealt with capacity restrictions and uncertainties during scheduling and project management, some literature research about capacity planning, dynamic scheduling and project management is done in this chapter.

Planning and scheduling of projects can be divided into 3 sub-processes, which are product configuration, project management & design planning and master production, shop floor & assembly scheduling, which are shown in figure 31 (Adrodegari et al., 2015).

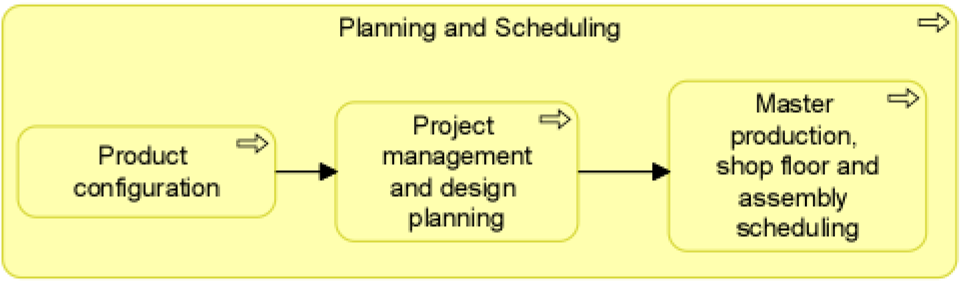

Figure 31. Planning & scheduling sub-processes. After (Adrodegari et al., 2015).

Planning is known at multiple levels. According to Adrodegari (2015), production planning can be divided into planning at factory level and at department level. At factory level, capacity loading, lead times and activities budget are monitored. At department level, more detailed order scheduling is done (Adrodegari et al., 2015). These production planning levels are shown in figure 32.

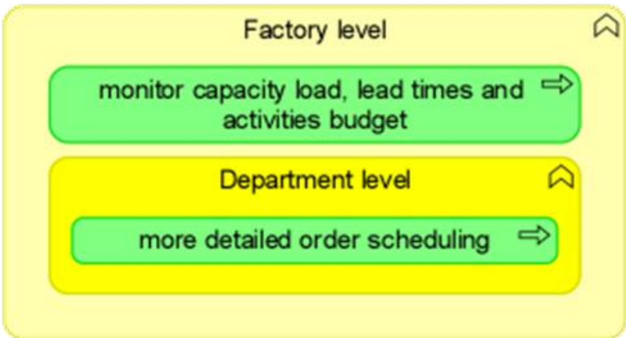

Figure 32. Production planning levels. After (Adrodegari et al., 2015).

Planning and scheduling is part of project management and is included in a project life cycle.

5.1. Project life cycle and planning

In general projects follow a project life cycle of 5 phases, namely order acceptance, process planning, scheduling, execution and evaluation & service. In the order acceptance phase, prices and delivery times are agreed. After the order acceptance phase, project activities are specified in the process planning phase. The specified project activities are scheduled into a detailed project schedule in the scheduling phase (Gademann and Schutten, 2005). After activities are scheduled, the activities are executed in the execution phase. In the end, the project is evaluated and serviced in the evaluation and service phase (Gademann and Schutten, 2005).

In general, the performance of production planning and scheduling is measured by the customer satisfaction and production costs. To measure the customer satisfaction, the customer service level is measured, which is the fraction of customer orders that is filled on or before their due dates. In terms of production costs, the inventory costs should be minimized. On the one hand, inventory of purchased materials should be minimized, while on the other hand, materials should be on time for production (Sawik, 2007). In general, planning issues are most important early in the project implementation (Herroelen, 2005).

In both the order acceptance and the scheduling phases, capacity management is important (Gademann and Schutten, 2005). Because of lean management concepts, capacities have been cut down and project scheduling is increasingly important (Tormos and Lova, 2003). Decisions made in the order acceptance phase about prices and delivery times are very important, since quoted prices and delivery times determine whether a project will be gained by the organization and if the project is profitable (Gademann and Schutten, 2005). In general, projects involve activities, which require one or more skills, for which one or several resources are needed. These resources are available in limited quantities and can meet a single and specific requirement (Koné et al., 2011; Almeida, 2019). Projects often deal with resources that master a wide range of skills, especially in case of human resources (Almeida, 2019). Good insight into available and required capacity of resources is required for quoting realistic prices and realizable delivery times (Gademann and Schutten, 2005).

However, in the order acceptance phase, accurate knowledge of resource capacities is not available, when due dates are committed. In that phase Rough Cut Capacity Planning (RCCP) is used as an analysis to test the availability of production facility capacity to ensure that at least the critical resources are sufficient to complete the project within time and cost limits (Baydoun et al., 2016; Sugarindra and Nurdiansyah, 2020). In that way, RCCP validates MPS and compares the available and required capacity to determine whether a production schedule requires non-regular capacity (Sugarindra and Nurdiansyah, 2020).

Rough Cut Capacity Planning (RCCP) is for roughly matching the available and the required capacities. RCCP supports in important aspects, such as order acceptance, capacity requirements and the use of non-regular capacity (Gademann and Schutten, 2005; Sugarindra and Nurdiansyah, 2020). At RCCP, early in the product life cycle, decisions are made about due dates, milestones of projects, overtime of work levels, subcontracting and required capacity levels, which are used as input later on in the process for Resource Constrained Project Scheduling Problem (RCPSP) at operational level (Herroelen, 2005; Leus and Herroelen, 2010). At this level, overtime is planned, subcontracting is done and additional staff is hired to exploit capacity flexibility (Herroelen, 2005).

For capacity planning, aggregate data of available and required capacity is used. When an order is received the project is broken down into jobs for roughly planning the project including investigating capacities (Gademann and Schutten, 2005). In RCCP all jobs from all projects are roughly planned. For RCCP, estimations of required resource capacities for each job and precedence relations which exist between jobs are the restrictions (Gademann and Schutten, 2005; Almeida, 2019).

In RCCP it is assumed that an equal fraction is spent on job J_j in week t on all resources, which is realistic in capacity planning since the activities in the jobs are in general multi-resource activities. If spending equal fractions is not possible, at planning level, jobs can be split into smaller jobs (one for each resource). The fractions may differ per week (Gademann and Schutten, 2005).

Later in the process, when project activities are specified, jobs are divided into activities and a more detailed planning can be made. For a more detailed planning, scheduling is used (Gademann and Schutten, 2005). With assistance of the prescheduled project timetable, generated by RCCP, managers can determine an optimal schedule (Tang et al., 2018). First jobs are subdivided into activities, which will be scheduled by the Resource-Constrained Project Scheduling Problem (RCPSP) (Gademann and Schutten, 2005).

Scheduling can be described as the allocation of resources over time to perform a collection of tasks (Koné et al., 2011; C. Hicks et al, 2007). The resulted schedule specifies the sequence and timing of the tasks (Hicks et al., 2007). By scheduling and sequencing, the goal is to allocate scarce resources optimal to activities over time (Herroelen, 2005). Scheduling helps realizing preset project management objectives and the resulted schedule aims at satisfying one or more of these objectives (Koné et al., 2011; Tang et al., 2018). Therefore, generating a reliable project schedule is an important goal in project management (Tang et al., 2018).

RCPSP is useful for scheduling a set of non-preemptive activities and assigning resources to it subject to minimizing the makespan/ completion time/ project duration (Almeida et al., 2019; Palacio and Larrea, 2017; Tormos and Lova, 2003; Leus and Herroelen, 2010). By using RCPSP a project is scheduled subject to constraints regarding the precedence relations of activities and constraints for the use and availability of finite renewable resources needed (Riedler et al., 2020; Koné et al., 2011; Almeida et al., 2019; Palacio and Larrea, 2017; Leus and Herroelen, 2010; Herroelen, 2005).

At RCPSP in the detailed project schedule, it is decided when specific activities are performed by which persons and which machines (Leus and Herroelen, 2010).

The interrelationship between RCCP, RCPSP and other planning and scheduling levels are shown in figure 33. Management levels can be divided into strategic, tactical and operational level. Moreover, planning can be divided into 3 different categories, namely technological planning, resource capacity planning and material coordination (Leus and Herroelen, 2010; Herroelen, 2005).

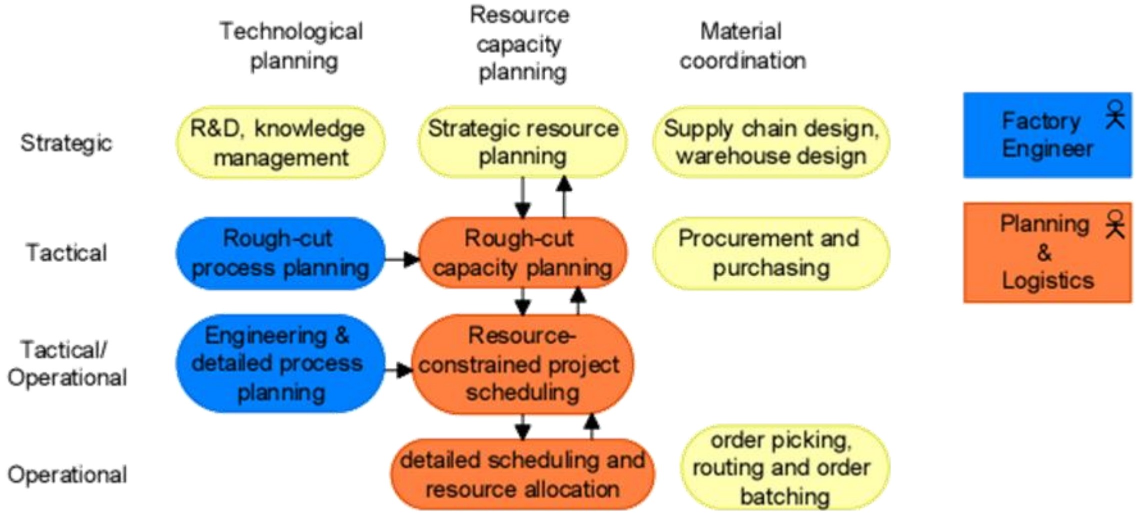

Figure 33. Interrelationships of planning and scheduling at different levels and different categories. After (Leus and Herroelen, 2010; Herroelen, 2005).

Besides interrelationships of planning methods at different management levels or at different categories, output of planning methods can be used as input for other planning methods. In figure 34, the interrelationships of among others MPS, MRP, RCPSP and RCCP are shown in a feedback loop.

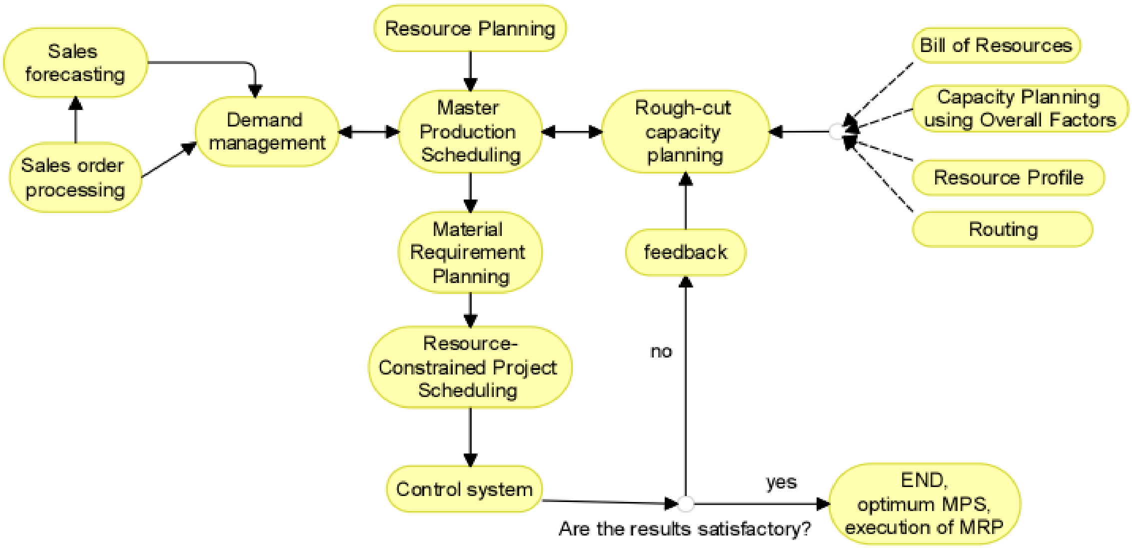

Figure 34. Feedback loop of planning methods which use each other's output as input. After (Vila Gocalves Filho and Astorino Marcda, 2001; Li et al., 2000; Zobolas et al., 2008).

5.2. MPS, MRP and PRP

MPS focuses on production scheduling based on long term plans, while MRP focuses on material and inventory planning based on production scheduling. Based on literature, these planning methodologies are described below.

5.2.1 Master Production Scheduling (MPS)

Master Production Scheduling coordinates production and marketing and translates companies' long term plans into goodsflow control decisions (Giesberts, 1991). It is common that companies' plans consist of targets/goals for their end-products. These goals are used as constraints in determining what quantities of the end-products have to be produced (Venkataraman, 1994). By using MPS, management decisions can be incorporated in determining production and delivery (Giesberts, 1991).

MPS specifies the anticipated production schedule for end products, which is called the master production schedule (Giesberts, 1991; Hill et al., 2000). The master production schedule is a production plan, which is prepared by forecasts and later on divided into requirements for end products (King et al., 1988). Besides requirements for end products, on-hand inventory and scheduled receipts of end-products are part of the master production schedule (Jodlbauer et al., 2019). The master production schedule specifies the production of end products or product options for specific time horizons of the planning horizon (Giesberts, 1991; Venkataraman, 1994; Mohebbi et al., 2007; Bakke et al., 1993). The master production schedule is based on actual and anticipated demand requirements (Giesberts, 1991; Venkataraman, 1994; Mohebbi et al., 2007). Anticipated demand requirements are based on forecasts of demand management, which provides production planning with demand information based on historical data, market information and marketing activities.

The master production schedule is restricted by budget and capacity limitations (Giesberts, 1991). The goal of a master production schedule is to balance product demand of customers with the product available supply by production schedules and inventory (Hill, et al., 2000). The objective of MPS is minimization of total production costs and maximization of production output (Li et al., 2000).

The master production schedule determines the production plan for specific products and transfers into Material Order Planning (Giesberts, 1991). Furthermore, MPS computes the levels of safety stock (Thevenin, 2020). MPS is required for MRP, since MRP requires specified delivery times and order quantities from the forecasted demand (Segerstedt, 2006). Moreover, MPS is important for capacity planning (Bakke et al., 1993).

At make-to-stock companies with a large number of end-products and a low predictability of demand, maintaining MPS requires severe effort (Giesberts, 1991).

5.2.2. Material Requirement Planning (MRP)

Material Requirements Planning (MRP) is a philosophy, technique, management and control method designed to minimize inventory investment, to maximize production efficiency and to improve customer service (Sagbansua, 2010; Fox et al.,1977). MRP relates inventory planning to production scheduling and deals with difficulties of both inventory and production scheduling (Sagbansua, 2010; Yeh, 1997).

The difficulty of inventory scheduling includes the need for keeping the inventory levels as low as possible, while sufficient safety stock of independent demand products are required to eliminate disruptions and delays. For dependent demand products, there is no need for safety stock. Therefore, a lack of distinction between dependent and independent demand will result in higher levels of inventories (Sagbansua, 2010). For both dependent and independent demand, it is important to determine lot sizes of materials, such that ordering and holding costs are minimized (Sagbansua, 2010).

Furthermore, in situations of variable lead times, it might be useful to make use of safety lead time. By using safety lead time, materials might arrive earlier than needed, but delays of other operations, resulting in losses and extra costs, are eliminated (Sagbansua, 2010). MRP is dealing with these difficulties, since the main focus of MRP is determining materials required for production by quantity and time and managing inventory waste by generating inventory information, in order to determine lot sizes and safety stock of materials (Benton et al., 1998; Thevenin et al., 2020; Yeh, 1997).

MRP starts with the schedule for the final product, which is received from the MPS, and translates the demand for the final products into a schedule with requirements for the raw materials and the coordination of the flow of materials to ensure timely delivering (Sagbansua, 2010; Mohebbi et al., 2007; Yeh, 1997). MRP controls whole manufacturing systems from purchasing till shop floor management (Benton et al., 1998). The material requirements planning system generates a complete schedule of materials required for manufacturing based on forecasted demand and/or sales orders for a finished product (Fox et al., 1977). This schedule includes a detailed list of what materials are required, required amounts of each material and when materials are needed subject to the lead time of both releasing purchase and job orders (Fox et al., 1977; Sagbansua, 2010). Scheduling by MRP is thus based on the materials which are needed and when these materials are needed (Plenert, 1999).

The main driver of the MRP system is MPS (Mohebbi et al., 2007). Requirements for each planning period are determined by exploding the MPS through a bill of material, a main schedule showing when and how much of the final products are needed, and an inventory records file showing how much inventory is at hand or how much is ordered (Sagbansua, 2010; Mohebbi et al., 2007;

Segerstedt, 2006). Output of MRP are planned order schedules, order confirmations, changes, performance control reports, planning reports and exception reports (Sagbansua, 2010). MRP considers only on-demand products, predefined parameters for safety stock, predefined lot-sizing policies and product specific constant lead times. MRP makes use of backward scheduling and capacity planning is not included (Jodlbauer et al., 2019).

Advantages of MRP: MRP is a very coherent and simple logic, which makes it popular in practice (Mohebbi et al., 2007). MRP has a easily comprehensible algorithm for scheduling production orders and is adaptable to dynamic demand fluctuations (Jodlbauer et al., 2019). MRP works well as a tool for managing materials (Li et al., 2000). MRP can predict material requirements for both purchasing and manufacturing for any MPS scenario (McCarthy et al., 2002). Benefits of MRP for production and assembly operations are among others low levels of in-process stocks, a possibility to track the component needs, a possibility to evaluate the capacity requirements suggested to the main schedule and a possibility of distributing the production time (Sagbansua, 2010). In case of minimal capacity constraints, production control of MRP systems is adequate (McCarthy et al., 2002).

Disadvantages of MRP: Even more effort is required to control production if resources become more heavily loaded and/or MPS fluctuations increases (McCarthy et al., 2002). In the context of capacity, MRP is a less attractive proposition to deal with, since it neglect capacity constraints and calculates with unlimited capacity (Li et al., 2000; Jodlbauer et al., 2019; Thevenin et al., 2020; Sagbansua, 2010; Benton et al., 1998; Yeh, 1997). MRP is taking a deterministic view of operational conditions that are inconsistent with realities of production environments, which often consist uncertainty of operations. As a result, that the plans of the MRP systems are inadequate or even infeasible (Mohebbi et al., 2007; Thevenin et al., 2020; Jodlbauer et al., 2019; Benton et al., 1998). Consequently, additional planning effort is required at the production control level and adjustments in planned orders have to be done during implementation to reconcile these inconsistencies of nondeterministic drivers such as demand, procurement lead time, production yield, production lead time and limited production capacity (Mohebbi et al., 2007; Sagbansua, 2010; Thevenin et al., 2020; Jodlbauer et al., 2019).

5.2.3. Project Resource Planning (PRP)

The project-related variant of MRP, which is commonly used in Engineer-to-Order (ETO) production, is Project Requirements Planning (PRP) (Rensburg van, 2008; Little et al., 2000; Little et al., 2001). In ETO resources are scarce, which results in increasing importance of taking the existing work load and forecast capacity projections into account for determining the due date for new orders. Otherwise, orders are likely to be late or requires overwork (Little et al., 2000; Little et al., 2001).

At PRP, every new order is considered as a project and each main element of production is scheduled on a forward scheduling (Little et al., 2000; Little et al., 2001). To get information about available capacity for a project, a project database is needed, which includes future projects and projects the company has experience with (Rensburg van, 2008). For every project, PRP calculates, based on the customer requirements, what activities have to be performed, how many of every specific product are required, what the complexity levels are and what the required durations are (Rensburg van, 2008; Cannas et al., 2018). The complexity and durations of activities are calculated by identifying associations between order characteristics and the average lead time needed to fulfill these tasks in historical data of previous orders (Cannas et al., 2018).

Based on the required tasks, its required durations, other orders and capacity constraints, completion due dates are established (Little et al., 2000; Little et al., 2001; Cannas et al., 2018). Consequently, based on a backward computation, the start and end dates of activities, with respect to meet the delivery date for the project, are defined (Cannas et al., 2018). PRP checks if required resources for future projects are available and ensures that these resources are arranged on time (Rensburg van, 2008).

5.3. Capacity planning

The Master Production Schedule should be feasible, which means that components should be produced within the available capacity. Therefore, it is desired to have a planning tool which efficiently considers capacity and MRP explosion. Master schedulers must be optimizers to balance conflicting goals of low inventories and efficient utilization of capacity (Clark, 2003).

Capacity problems fluctuate between overload and idleness problems. In case of overload, the profitability is reduced due to over-proportional high costs to deal with overload, while in case of idle resources money is lost due to low utilization (Bakke & Hellberg, 1993). Moreover, resource limitation results in resource dependencies and extending overall schedule durations (Shu-Shun and Shih, 2009). Furthermore, material management may represent a problem, because of uncertainties in long supplier lead times. Due to these uncertainties, inventories are high or critical materials and components are lacking, which results in delay of operations (Bakke & Hellberg, 1993). The importance of resources can be determined by resource productivity (Shu-Shun and Shih, 2009).

In general, first computational tasks are scheduled, which are done intern, and next network tasks are scheduled, which will be done extern (Belter et al., 2021). Scheduling consists of 2 operations, first resource- and time-feasible allocations of resources to network tasks have to be found and subsequently, start and finish times of all network tasks have to be determined (Belter et al., 2021).

Factors which have influence on capacity planning are:

- Alternative routings
- Replanning of production orders
- Due date observance is an important competitive parameter
- Mix of end-products to be produced fluctuates considerably
- Unique products/projects create a variable load for construction and work preparation of new products for manufacturing and assembly
- Demand
- Periodic capacity
- Available resources
- Bottleneck resources are often variable and it is difficult to predict the unstable character of BOMs
- Safety stock
- A high number of products is manufactured in small quantities at irregular intervals, which result in difficulties in establishing a perfect flow-oriented layout
- If backlogging is allowed or not: allowing backlogging create more flexibility in planning solutions
  (Bakke & Hellberg, 1993; Kim, Kim, 2001)

In case of capacity shortages, the following actions can be done:

- Buy capacity by subcontracting several orders
- Hiring additional personnel
- Work longer, in more shifts and/or add weekend shifts (overtime)
- Cancel orders

- Delay product delivery
- Re-arrange the production plan to balance the system and produce some orders earlier if capacity and storage space allows

(Zobolas et al., 2008; Bakke et al., 1993)

In case of capacity surplusage, the following actions can be done:

- Schedule planned holidays
- Schedule education programs for personnel

(Bakke et al., 1993)

Improvements for capacity planning are:

- Keeping the MPS up-to-date
- Integration of different planning horizons into one system
- Customer order oriented capacity planning and order release
- Capacity controlling for having an overview of the available capacity
- Capacity planning for engineering tasks (manpower)
- Reorganizing subcontracting or integration of subcontractors into the planning process (Bakke & Hellberg, 1993)

MPS can play a key role in capacity planning by including requirements from:

- Capacity planning using overall factors (CPOF)
- Capacity Bills
- Resource Profiles
- Capacity Requirements Planning (CRP)
  (Bakke & Hellberg, 1993)

5.4. Project planning

At ETO manufacturing, a high variety of products are manufactured and assembled in low volumes to satisfy individual customer specifications. Therefore, ETO products are also called customer oriented projects. Most often, manufacturing customer oriented projects include some construction and work preparation activities, which results in long leadtimes (Hicks et al, 2007; Barbosa et al., 2018). Therefore, most ETO companies use project planning methods for high-level scheduling of projects. For planning factory-based manufacturing and assembly of components and systems, in general Manufacturing Resources Planning (MRPII) is used (Hicks et al., 2007).

At ETO manufacturing demand fluctuates and tends to occur in large discrete units (Hicks et al., 2007; Barbosa et al., 2018). Furthermore, in both MTO and ETO manufacturing, the environment is dynamic, in which orders may be modified, canceled and new orders are placed continuously during the production process (Sabuncuoglu and Kizilisik, 2003; Sun and Xue, 2001; Sawik, 2007). Moreover, process durations may be variable for projects (Barbosa et al., 2018).

In ETO manufacturing project-based orders are manufactured, which includes much variability and uncertainty. This variability and uncertainty in project activities results in schedule disruptions and complexity that requires management to handle all processes from design & engineering to production & delivery (Adrodegari et al., 2015; Leus and Herroelen, 2010).

5.4.1. Uncertainties

Industrial scheduling contain much load and capacity uncertainties which are derived from unexpected events/ other uncertainties, such as:

- MPS uncertainties
- Capacity uncertainties and loss: resources may become unavailable, resource failures may occur and workers may be absent because of illness
- Load uncertainties: activities may take more or less time than originally estimated
- Scheduling methodology uncertainties
- Work preparation uncertainties
- Subcontracting and supplier uncertainties: material may arrive behind schedule/ deliveries of suppliers may be late
- Variability in project parameters, estimates, processes, objectives/priorities/trade-offs, relationships with project partners
- Uncertainty of external influences
  (Bakke et al., 1993; Leus and Herroelen, 2010; Palacio and Larrea, 2017; Herroelen, 2005)

In industrial scheduling, uncertainty is encountered in:

- Work content
- Occurrence of activities
- Resource availability
- Release dates
- Due dates
  (Herroelen, 2005)

By using a project uncertainty profile, a qualitative characterization of degree to which each type of uncertainty may affect the project can be analyzed (Herroelen, 2005).

Because of uncertainties and variability in project activities, the activity durations contain some time deviation. As a result of time deviation in estimated activity durations, project finish dates and project total costs will change. To overcome unpredictable deviations, it is recommended to consider uncertainty in the project scheduling process (Palacio and Larrea, 2017). This uncertainty can be represented by stochastic activity durations (Leus and Herroelen, 2010). Stochastic project scheduling can deal with scheduling project activities with uncertain durations. By using stochastic project scheduling, the expected project duration under precedence and resource constraints can be minimized (Herroelen, 2005).

To deal with capacity problems and uncertainties, it is desired to have dynamic regulation of capacity and increasing flexibility requirements. For dynamic capacity planning, it is desired to have a correct identification of bottlenecks. Capacity planning is important for all departments/sections which are involved in the completion of customer orders (Bakke & Hellberg, 1993).

To tackle uncertainty in project scheduling, it is desired to have robust schedules. Robust schedules are able to cope with variations in time duration of some activities without delaying the project finish date (Palacio and Larrea, 2017). Considering robustness in project scheduling is useful if undesirable conditions are expected during project execution or if accurate information about probability distributions for activity durations are not available (Palacio and Larrea, 2017).

5.4.2. Dynamic planning

Since industrial scheduling problems in make-to-order (MTO) and engineer-to-order (ETO) environments are dynamic, it is desired to have a scheduling system which both include a predictive and a reactive mechanism. The predictive mechanism is desired for schedule generation and the reactive mechanism is desired for control (Sabuncuoglu and Kizilisik, 2003; Sun and Xue, 2001; Sawik, 2007). In figure 35, the phases in which a predictive and a reactive mechanism are desired are shown.

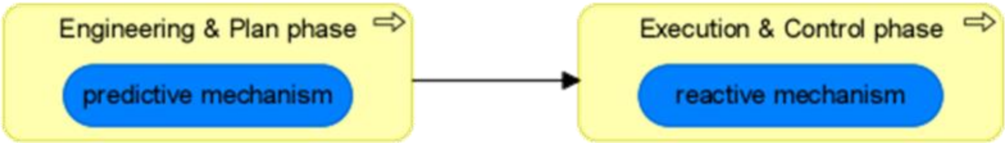

Figure 35. Scheduling including predictive and reactive mechanism. After (Adrodegari et al., 2015).

5.4.2.1. Work preparation

In the Engineering & Plan phase in which work preparation is done, the performance is dependent on multiple factors, namely:

- The design/engineering workload
- The project type
- The design reuse
- Outsourcing
- The complexity
- Experience/knowledge of technology
- Human resources: productivity is dependent on experience and training

(Barbosa et al., 2018)

For work preparation activities, it is desired to monitor the due date observance. It would be useful that capacity for the required resource will be increased if the average due date deviation exceeds a certain time (Bakke et al., 1993).

To fulfill customer orders, coordination between engineering & manufacturing is a key (Barbosa et al., 2018).

5.4.2.2. Predictive scheduling

Predictive scheduling creates an optimal predetermined production schedule based on given requirements and constraints prior to the production process, which is modified by reactive scheduling during the manufacturing process to deal with unexpected changes in the production environment. Reactive scheduling algorithms are used in dynamic scheduling, in which the existing schedule is updated by reacting to the occurrence of unpredictable events (Sun, Xue, 2001; Sawik, 2007; Hicks et al., 2007).

Since it is desired to have a robust baseline schedule, it is desired that the predictive scheduling methodology includes a proactive mechanism, which incorporates a degree of anticipation of variability during the project execution (Herroelen, 2005). Moreover, baseline schedules should consider reactive policies, such as rescheduling, reallocation of resources and activity crashing (Herroelen, 2005).

The resulting schedule of predictive scheduling is called the preschedule or the baseline schedule. This baseline schedule is used as a guideline by all persons engaged for executing the project (Leus and Herroelen, 2010). The most important functions of the baseline schedule are:

- Allocating resources to different jobs to optimize some measure of performance
- Quoting competitive and reliable due dates
- Scheduling the activities in consultation with all parties within the supply chain
- Agree on time windows for work to be done by subcontractors
- Share production schedules with suppliers on a continuous basis
- Making cashflow projections
- Serving as a guideline for planning external activities such as material procurement, preventive maintenance and committing shipping dates towards customers
- Measure performance of both management and shop floor personnel
- Project monitoring & control: without a predetermined schedule, process control of the project is not possible
  (Leus and Herroelen, 2010; Herroelen, 2005; Tang et al., 2018)

In multi-project environments, the baseline schedule should be agreed by all parties before the start of the project, such that adjustments can be made on time if needed (Leus and Herroelen, 2010).

5.4.3. Factors for projects

Factors which have impact on project managers' decisions:

- Makespan
- Revenues
- Costs
- Resources leveling
- Uncertain project duration
  (Palacio and Larrea, 2017)

Classical problems in project scheduling are:

- Resource allocation problem: Allocating limited resources to various activities in a project to minimize the project duration
- Resource leveling problem
- Time/cost trade-off problem
  (Tang et al., 2018)

Critical success/failure factors for projects are:

- Project scheduling is the major factor in predicting success or failure
- Initial planning: defining project mission, developing project/schedule plans, order acceptance
- Tactical operationalization: top management, support, personnel, technical tasks, monitoring and feedback, communication, trouble shooting
  (Herroelen, 2005)

To insert new activities into a project with constant resource allocation, resource flow networks can be used. In resource flow networks, transferring resources from one activity to another are immediately recorded (Leus and Herroelen, 2010).

5.4.4. Rescheduling

Updating the schedule can be done periodically or just when some events occur, and dynamic scheduling can be done by incremental planning or regenerative planning. At incremental planning, the already scheduled orders remain the same and only new orders are planned, while at regenerative planning all orders are rescheduled. Unless this difference, both planning methods have a common objective which is minimizing costs (Hicks et al., 2007). In general, with using regenerative planning, arrival of new orders can have large effects upon existing schedules. Therefore, it is recommended to use regenerative planning only if new orders are urgent or large. Otherwise, it is recommended to use incremental planning (Hicks et al., 2007).

The generated schedule created by the predictive mechanism may be changed to reflect changes of production orders, such as canceled orders which should be removed and new (urgent) orders which should be inserted into the schedule, and manufacturing conditions, such as disturbance events of resources and sickness of workers, during the production process (Sun, Xue, 2001).

Before rescheduling customer orders, orders are first ranked on urgency. In this ranking, orders which are due-time based have priority over earliest-delivery-time based orders. Products for which 2 or more customer orders have delivery times close to each other, may be processed together. Moreover, to satisfy precedence and capacity constraints, a breakdown of net-requirements for manufacturing is made. To satisfy the net-requirements, while improving the rescheduling efficiency, the sequence of tasks for each to-be-rescheduled order and resources allocated to the rescheduled tasks remain the same for orders which have to be rescheduled due to changes of customer orders (Sun, Xue, 2001; Bakke et al., 1993).

In case of changes of manufacturing resources, which affects individual orders, the decision maker is informed about the problems and the expected due-date deviation. In that case, if possible, tasks which are directly affected by the resource are first moved to other resources without changing the timing parameter values of these tasks. If alternative resources are not identified, orders are postponed and rescheduling is done based on the urgency ranking. For due-time-based orders which cannot meet the due-time constraint due to the changes in the manufacturing resources, directly affected orders will be rescheduled with modified due-time values after all other due-time-based orders are rescheduled. To satisfy the net-requirements and improving the rescheduling efficiency, the sequence of tasks for each to-be-rescheduled order remains the same. If alternative resources cannot be identified for affected tasks, each rescheduled task is still allocated with the originally assigned resources to improve rescheduling efficiency (Sun, Xue, 2001; Bakke et al., 1993).

A project plan can be affected by control policies, system configuration, dispatching rules and buffer space (Kim, Kim, 2001).

5.5. Integrated system

It would be beneficial to have a planning system which contain integration between production scheduling and process control, which consist of a scheduling module, a simulation model and a controller, to have model predictive control. The scheduling module would be useful for identifying optimal production sequences, product quantities and corresponding production times for generating schedules with maximized operational profit per unit time. The generated schedules are passed to the controller. The controller would be useful for controlling the schedule and forward the schedule to the simulation model for execution. In the simulation model, system-related data and values of environmental parameters would be available, scheduling decisions would be implemented and movement & storage capacity would be represented. Furthermore, it would be useful to have incorporation of a dynamic process model for identifying transition time, such that the system contains a closed-loop implementation strategy (Sabuncuoglu and Kizilisik, 2003; Baldea et al., 2015; Sun, Xue, 2001).

It is desired to have a system which bridges the gap between MPS and shop floor control systems, such that a detailed capacity planning can be made by the system. With such a system, detailed decisions can be made on time since information from the system is clear input for weekly discussions between departments/sections. Furthermore, with such a system, information can be used for influencing customers to place orders at favorable periods of time from a capacity point of view and for evaluating consequences of chosen priorities with high precision. Moreover, information from the system can enable identifying problem areas and act on time by increasing or decreasing capacity (Bakke et al., 1993).

It would be useful to use the database of such an integrated system for among others:

- Identifying bottlenecks and non-bottlenecks
- Simulating probable lead times and due date deviation for the complete production plan, which can be displayed for both individual work orders and complete customer orders
- Simulating consequences of changes in capacity, delivery dates and production program
- Computing lead times based on the actual mix of the load by a scheduling technology which is flow oriented
- Analyzing and comparing plan-alternatives
  (Bakke et al., 1993)

5.6. Critical functionalities

Moreover, some critical functionalities for ETO manufacturing are:

Planning:	Project management:
• Resource allocation	• Project specification, project estimation, project activities modification
• Activity planning	• Project monitoring and control/activity status monitoring: reporting performance, taking corrective actions, taking preventive actions in anticipating possible problems
• Activity plan representation	• Project planning: deadlines completion of deliverables

(Adrodegari et al., 2015; Herroelen, 2005)

Project management and production planning are useful in ETO manufacturing to optimize:

- Project sequences
- Activities scheduling
- Project status monitoring
  (Adrodegari et al., 2015)

Project portfolio management and analysis can be used to:

- Maximize resource utilization
- Eliminate duplicate projects
- Collect organizational knowledge

- Institute best practices
  (Herroelen, 2005)

Using project portfolio management and analysis can result in better communication, a streamlined resource management and improved productivity (Herroelen, 2005).

5.6. Conclusions of literature research

In this chapter, literature research is done about project management, project planning, dynamic planning and capacity planning. Planning of projects consist of multiple processes and projects follow a lifecycle of multiple phases. Resources for performing projects are limited. Therefore, capacity planning is important for projects, especially during order acceptance and scheduling. RCCP is suggested in literature to use during order acceptance for roughly planning capacity and making decisions about due dates, milestones of projects, overtime of work levels, subcontracting and required capacity levels.

After project activities are specified in process planning, jobs are divided into activities and scheduling is done by RCPSP. Scheduling helps realizing project management objectives and is the allocation of resources over time to perform tasks. At RCPSP, projects are scheduled subject to constraints and decisions are made about when specific activities are performed including start and finish times and by which resources (both machines and employees).

Literature shows interrelationships between multiple planning methodologies. For example, MPS, in which a master production schedule is prepared by forecasts and demand is divided into requirements for supply, and RCCP have interrelationships with each other. To determine when materials have to be ordered for the prepared production schedule by MPS, MRP is used. MRP translates demand for final products into a schedule with requirements for raw materials and the coordination of the flow of materials to ensure delivery on time, which includes required materials and when these materials are required.

Another scheduling related issue served in literature is the need for balancing conflicting goals of low inventories and efficient utilization of capacities and the importance of safety stock for dealing with uncertainties. For dealing with uncertainties, capacity problems and unexpected modifications, literature suggests increasing flexibility, using dynamic regulation and to eliminate uncertainties by identifying bottlenecks.

Scheduling in a dynamic environment can be done by dynamic scheduling including a predictive and a reactive mechanism. During predictive scheduling, an optimal predetermined production schedule is generated, which can be used as a guideline for a project. The generated schedule by predictive scheduling can be modified by reactive scheduling to deal with unexpected changes.

In literature, integration between production scheduling and control systems is recommended for detailed capacity planning and simulating among other consequences of modifications and analyzing plan alternatives. It is desired that a scheduling module for generating a schedule, a controller for controlling and forwarding the schedule and a simulation model are included in an integrated system. Moreover, an integrated system may be beneficial as input for intern discussions and for having influence on placing customer orders.

Last, but not least, planning and project management functionalities are critical for projects as mentioned in literature. For projects it is beneficial to have insight into project sequences, activity scheduling, project status monitoring, resource allocation and project specification. Project portfolio management and analysis may result in better communication, a more streamlined resource management and improved productivity.

To conclude, project management and planning methodologies are much discussed in literature. For this research especially RCCP and dynamic scheduling are relevant for scheduling and decision making. These planning methodologies are used in chapter 6 for designing a baseline model. Other relevant findings in literature are integrations between scheduling and control systems and functionalities for project planning and project management. These findings are relevant as recommendations for implementing in the new ERP system.

Chapter 6. Solution design

In this chapter, we intend to come up with a solution for dealing with the output of an ERP system which calculates with infinite capacity, while limited capacity is available and dual source is used. Furthermore, we intend to include both capacity limitations and required work preparation tasks. Moreover, we intend to come up with a solution to get insight in engineering population and to deal with uncertainties and unexpected events.

As mentioned earlier in this report, the current ERP system calculates with infinite capacity, while limited capacity is available. By calculating with infinite capacity, orders are planned over each other, which results in an infeasible planning. On the other hand, by calculating with finite capacity, processes are postponed, which results in much delay.

In the past, the company has chosen for a system which calculates with infinite capacity in combination with an order planner which decides what will be produced and what will be purchased. The order planner makes a planning by hand based on the output of the system.

6.1. Dealing with limited capacity

It would be useful if the order planner could use a tool or simulation which gives a suggestion for planning regarding manufacturing and outsourcing. In literature, Rough Cut Capacity Planning is suggested for roughly planning orders and determining required non-regular capacity based on capacity limitations and due dates. During this research, a linear model is designed which can be used for deciding dual source assignment, machine assignment and determining due dates for production steps and engineering tasks. RCCP is used as a basis for this model and expanded with decision making procedures of VDL ETG Almelo, such that the model is applied to intern processes and considers process related constraints.

Linear Programming is a commonly used algorithm in Operations Research and optimizes the given mathematical objective by making decisions for decision variables. By linear programming, relations between decision variables and parameters can be expressed in linear equations and constraints can be expressed in linear equations as well. The goal of the tool is to make a planning, which meets constraints, regarding capacities and due dates, and minimizes the costs of purchased orders and/or outsourced process steps.

6.1.1. Routings and categories

First, deciding if an order will be (partly) produced intern or purchased is dependent on the category in which the order is categorized and deciding if a process step of the order will be performed by an intern machine or outsourced is dependent on the chosen routing. In this context, a routing indicates machines and outsourcers visited by a production order. In a routing, for each process step the assigned machine or the assigned outsourcer is indicated as location. For every process step of an order multiple intern and/or outsourcing routings are possible. The possible routings for producing a product are reported into the production folder. These routings may include multiple outsourcers in case of outsourcing process step j and/or multiple machines in case of performing process step j intern.
For each routing r, parameter $routing_{ojr}$ indicates if an intern machine is assigned to perform process step j of order o ($routing_{ojr} = 1$) or if an outsourcer is assigned to routing r of process step j of order o ($routing_{ojr} = 0$). If an outsourcer is assigned to perform a process step in the routing, outsourcing this process step is called outsourcing in folder.

To illustrate, we use an example problem with 5 orders, 5 process steps and 4 routings. To illustrate, the following table indicates if intern machines and/or outsourcers are included into routings for performing process steps of orders of the example problem.

Order number		**Intern machines and/or outsourcers assigned**
1	**Process step**	
	1	Machines 1 & 4
	2	Machines 1 & 3 and outsourcer
	3	Machines 2 & 4
	4	Outsourcer
	5	Machines 1 & 3 and outsourcer
2	**Process step**	
	1	Machines 2, 3 & 4 and outsourcer
	2	Machines 1 & 2
	3	Outsourcer
	4	Machines 1 & 3
	5	Machines 1 & 2
3	**Process step**	
	1	Outsourcer
	2	Machines 1 & 3 and outsourcer
	3	Machines 1, 3 & 4 and outsourcer
	4	Machines 2 & 4 and outsourcer
	5	Outsourcer
4	**Process step**	
	1	Machines 2 & 3 and outsourcer
	2	Outsourcer
	3	Machines 2, 3 & 4 and outsourcer
	4	Machines 1 & 4 and outsourcer
	5	Machines 1 & 3 and outsourcer
5	**Process step**	
	1	Outsourcer
	2	Machines 2 & 4 and outsourcer
	3	Outsourcer
	4	Outsourcer
	5	Outsourcer

In the linear model, the intern machine which is assigned to a routing for performing a process step of an order is indicated by a binary value. For orders to which an intern machine is assigned, the following table indicates which intern machine is assigned to the routings 1 to 4 of the example problem used. The intern machine assigned is indicated by value “1” and intern machines which are not assigned to performing the process step of that order in the corresponding routing are indicated by value “0”. If less than 4 routings are assigned to process step j of order o, the same routing may be given multiple times in the table.

Besides intern routings, outsourcing routings are indicated in the table. If an outsourcer is assigned to a routing for performing a process step of an order, the assignment of intern machines are indicated by “0” for all intern machines, since neither intern machine is assigned if an outsourcer is assigned.

Routing \ order		1					2					3					4				
1	Process step																				
	1	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	1	0	0	0	assigned	0	0	0	1	assigned	0	0	0	1
	2	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	0	0	1	0	assigned	0	0	0	0	assigned	0	0	0	0
	3	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	1	0	0	assigned	0	1	0	0	assigned	0	0	0	1	assigned	0	0	0	1
	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
	5	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	0	0	1	0	assigned	0	0	0	0	assigned	0	0	0	0
2																					
	1	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	1	0	0	assigned	0	0	1	0	assigned	0	0	0	1	assigned	0	0	0	0
	2	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	1	0	0	0	assigned	0	1	0	0	assigned	0	1	0	0
	3	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	1	0	0	0	assigned	0	0	1	0	assigned	0	0	1	0
	5	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	1	0	0	0	assigned	0	1	0	0	assigned	0	1	0	0
3																					
	1	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
	2	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	0	0	1	0	assigned	0	0	0	0	assigned	0	0	0	0
	3	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	0	0	1	0	assigned	0	0	0	1	assigned	0	0	0	0
	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	1	0	0	assigned	0	0	0	1	assigned	0	0	0	0	assigned	0	0	0	0
	5	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
4																					
	1	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	1	0	0	assigned	0	0	1	0	assigned	0	0	0	0	assigned	0	0	0	0
	2	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
	3	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	0	1	0	0	assigned	0	0	1	0	assigned	0	0	0	1	assigned	0	0	0	0
	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	0	0	0	1	assigned	0	0	0	0	assigned	0	0	0	0
	5	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4	Machine	1	2	3	4
		assigned	1	0	0	0	assigned	0	0	1	0	assigned	0	0	0	0	assigned	0	0	0	0
5																					

	1	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
	2	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**
		assigned	0	1	0	0	assigned	0	0	0	1	assigned	0	0	0	0	assigned	0	0	0	0
	3	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
	4	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0
	5	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**	**Machine**	**1**	**2**	**3**	**4**
		assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0	assigned	0	0	0	0

Besides the intern machine which is assigned to perform a process step of an order, the above given table indicates if an intern machine or an outsourcer is assigned to perform the process step of the order in the corresponding routing. The color in which "assigned" is marked indicates if an intern machine or an outsourcer is assigned to perform the process step of the order in the corresponding routing. For process steps of orders for which an outsourcer is assigned to routing r, the word "assigned" is red marked in the table and for process steps of orders for which an intern machine is assigned to routing r, the word "assigned" is green marked in the table.
Therefore, the parameter values of parameter $routing_{ojr}$ are as follows:

If "assigned" is green marked, then $routing_{ojr} = 1$.

If "assigned" is red marked, then $routing_{ojr} = 0$.

Parameter $InternRoutingMachine_{ojcr}$ is used to indicate which intern machine is assigned to routing r to perform process step j of order o. Parameter $InternRoutingMachine_{ojcr}$ is a binary parameter and indicates if machine c is assigned to perform process step j of order o in routing r ($InternRoutingMachine_{ojcr} = 1$) or not ($InternRoutingMachine_{ojcr} = 0$).

For process steps of orders to which an outsourcer is assigned, neither intern machine is assigned, which means that for all machines c, $InternRoutingMachine_{ojcr} = 0$. For these process steps, outsourcers are selected and assigned to the outsourcing routings in production folders. However, for deciding what to perform intern and what to outsource based on intern machine capacity, it is not directly relevant which outsourcer is assigned to the routing. Because of simplicity reasons, the model does not include the assigned outsourcers.

Which routing becomes the chosen routing will be decided by the binary variable $Chooserouting_{ojr}$. $Chooserouting_{ojr}$ indicates if routing r is the chosen routing for process step j of order o, in which $Chooserouting_{ojr} = Bin(0{,}1)$ and $\sum_r Chooserouting_{ojr} = 1$. Routing r is chosen if $Chooserouting_{ojr} = 1$ and if $Chooserouting_{ojr} = 0$, routing r is not chosen.

While the decision for performing process steps intern or outsourcing process steps is dependent on the chosen routing, the decision for producing orders (partially) intern or purchasing orders is dependent on the assigned category of the order. Categories are assigned to orders based on the required technologies. The assigned categories of orders are reported in the ERP system.

The orders of the illustrated example problem are categorized to the following categories:

Order number	Category
1	1
2	1
3	3
4	2
5	5

The category to which an order is assigned indicates if a product of that order is always (partially) produced intern, always purchased or if a product of that order can be either produced intern or purchased. Products of category 1 are always (partially) produced intern, products of categories 4 and 5 are always purchased and products of categories 2 and 3 can be either produced intern or purchased. Therefore, deciding to produce order o (partially) intern or to purchase order o, is dependent on the category to which order o is categorized.

Relationships of the category to which order o is categorized and the decisions which can be made for order o with respect to producing (partially) intern or purchasing can be expressed by the following if-statements:

If products of order o are always (partially) produced intern, then it will be decided that order o will be (partially) produced intern. In this situation, at least 1 process step is performed intern and the responsibility of producing order o lies intern.

If products of order o are always purchased, then it will be decided that order o will be purchased.

If products of order o can be either produced intern or purchased, then the decision of order o can be either producing (partially) intern or purchasing.

In the model, the decision variable M_o is used to decide if order o will be (partially) produced intern ($M_o = 1$), or if order o will be purchased ($M_o = 0$). The category to which order o is categorized is indicated by the parameter cat_o in the model. In terms of M_o and cat_o, the above mentioned if-statements can be expressed as:

If $cat_o = 1$, then $M_o = 1$.
If $cat_o \geq 4$, then $M_o = 0$.
If $1 < cat_o < 4$, then $M_o = Bin(0,1)$.

These if-statements can be transposed into the following linear constraints for making a linear model:

$M_o \leq 2 - cat_o$
$M_o \leq 3/cat_o$

For products which can be purchased, suppliers are selected beforehand. If an order is purchased, the products of the order are divided over the preselected suppliers.

For process steps, a comparable decision variable is used in the model to determine if a process step will be performed intern or outsourced. In the model, decision variable M_{oj} is used to indicate if process step j of order o will be performed intern ($M_{oj} = 1$) or outsourced ($M_{oj} = 0$).

Dependent on the chosen routing and if an intern machine or an outsourcer is assigned to process step j of order o of the chosen routing, it is determined if process step j of order o will be performed intern ($M_{oj} = 1$) or outsourced ($M_{oj} = 0$). The dependency of $Chooserouting_{ojr}$ and $routing_{ojr}$ for M_{oj} can be expressed by $M_{oj} = \sum_r routingIntern_{ojr} * Chooserouting_{ojr}$.

M_o is the decision variable for deciding if order o will be (partially) produced intern or purchased and M_{oj} is the decision variable for deciding if process step j of order o will be performed intern or outsourced. M_o and M_{oj} are related to each other, in such a way that if at least one process step is performed intern, it is decided that the responsibility for producing the order is intern, which means that the order is manufactured (partially) intern. This can be expressed as $M_o \geq M_{oj} \ \ \forall o, j$.

In general, if it is decided that an order will be (partially) produced intern, most process steps will be performed intern, unless capacity is limited, and process steps can be both performed intern or outsourced.

The other way around, if multiple process steps can only be outsourced or if it is decided to outsource multiple process steps of an order, it may be more efficient to purchase the whole order. For every order, an input value for the maximum number of process steps which can be outsourced before it is more efficient to purchase the whole order can be given for parameter $maxprocessoutsourcing_o$. If it is more efficient to purchase the whole order is dependent on among others the complexity of the order, capabilities of outsourcers and the duration of process steps.

For orders of category 1, it is undesired to purchase the whole order because of strategic reasons, therefore, the maximum process steps which can be outsourced before it is more efficient to purchase the whole order is equal to the total number of process steps for order o. This can be expressed by $maxprocessoutsourcing_o = N$. For other categories, it is assumed that a list with selected suppliers, which are capable to produce the whole order, is available. For these orders, the value of $maxprocessoutsourcing_o$ can be estimated and filled in as a parameter, such that $maxprocessoutsourcing_o = integer$ and $0 \leq maxprocessoutsourcing_o \leq N$.

For the illustrated example problem, the following values for $maxprocessoutsourcing_o$ are given:

Order number	$\boldsymbol{maxprocessoutsourcing_o}$
1	5
2	5
3	4
4	3
5	2

To ensure that the number of single process steps which will be outsourced do not exceed the value of $maxprocessoutsourcing_o$, the following constraint is added to the model: $maxprocessoutsourcing_o + (1 - M_o) * 1000 \geq \sum_{j=1}^{N} (1 - M_{oj})$.

6.1.2. Objective

Besides considering restrictions for purchasing, producing and outsourcing, planning is focused on minimizing costs for purchasing and outsourcing. It is intended to minimize costs of outsourcing process steps and it is intended to manufacture the more expensive and complex parts intern.

The goal of the model is to make decisions about orders and its process steps in such a way that purchasing expensive and complex parts is minimized and that additional costs of outsourcing process steps are minimized. It is desired to minimize outsourcing process steps of/purchasing of complex parts, because of strategic reasons and quality control. Moreover, it is desired to minimize purchasing of expensive parts, since costs of purchasing expensive parts are high. It is intended to utilize the intern capacity optimally and make use of outsourcing for additional required capacity, in such a way that outsourcing is as cheap as possible.

Therefore, the objective is: $min \sum_{o=1}^{M} \sum_{j=1}^{N} \sum_{i=1}^{P} ((1 - M_o) * (O_{oi} * price_i * complexity_i) + (M_o - M_{oj}) * \left(c_{oj} + \frac{O_{oi}*price_i*complexity_i}{maxprocessoutsourcing_o+1}\right))$, in which c_{oj} indicates additional costs of outsourcing process step j of order o, O_{oi} indicates if order o consist of product i, $price_i$ indicates the price of a product of product i and $complexity_i$ indicates the complexity of product i. The values of $c_{oj}, price_i$ and $complexity_i$ are positive, therefore, $c_{oj}, price_i, complexity_i \geq 0$. The values of O_{oi} are 0 or 1, therefore, $O_{oi} = Bin(0,1)$.

In the following table, the products of the orders and the additional costs of outsourcing process steps of the orders of the illustrated example problem are given:

Order number	O_{oi} i= 1	2	3	c_{oj} j= 1	2	3	4	5
1	1	0	0	20	40	30	15	25
2	0	0	1	30	60	50	25	35
3	0	1	0	22	44	34	17	27
4	0	0	1	40	80	70	35	45
5	1	0	0	15	30	20	10	20

The price and complexity of the corresponding products of the illustrated example problem are given below:

Order number	$price_i$	$complexity_i$
1	5000	0.8
2	3000	0.4
3	4000	0.6

6.1.3. Work preparation tasks

Since the duration of finishing an order is dependent on both manufacturing steps and work preparation tasks, it is important to consider the work preparation for orders for which it is decided to manufacture (partially) intern ($M_o = 1$). The release date of the first manufacturing step is dependent on the tasks which have to be done during work preparation. Therefore, for making a planning it is required to make an estimation of the durations of tasks which have to be performed during work preparation.

In the model, the work preparation is divided into two steps, from which the first step is set as the release date of work preparation and the second step as the process duration of the work preparation. The first step includes precedence relations of purchasing and programming, which have to be performed by Factory Engineering before purchasing and programming can start with work preparation tasks.
Therefore, the release date of the work preparation trajectory of order o is given by: $r_o^w = round\left(\left(p_o^{P_{purchasing}} + p_o^{P_{programming}}\right) + CurrentWeek\right)$, in which $CurrentWeek$ indicates week number t of the moment that a decision is made if order o will be manufactured intern or outsourced. The value of $CurrentWeek = integer$, which is given as an input for the model.

The current week of the example problem, durations of the precedence activities of work preparation activities of orders of the example problem and the release week of the work preparation of orders of the illustrated example problem are given in the following table:

Order number	Current week	$p_o^{purchasing}$	$p_o^{programming}$	r_o^w
1	3	0.05	0.1	3
2		0.04	1	4
3		0.07	0.6	4
4		0.1	0.05	3
5		0.02	0.3	3

Tasks which have to be done in the second step of the work preparation trajectory are performed by both purchasing, programming and Factory Engineering (FE). The earliest possible completion time of work preparation is dependent on the section with tasks with the longest duration. Therefore, the duration of the work preparation trajectory of order o is given by parameter $p_o^w = \max(p_o^{LeadtimePurchasing}, p_o^{programming}, p_o^{FE})$, in which $p_o^{LeadtimePurchasing}$ is the leadtime for purchasing materials for order o, $p_o^{programming}$ is the duration of programming tasks for order o and p_o^{FE} is the duration of tasks of Factory Engineering for order o during work preparation.

For the illustrated example problem, durations of work preparation tasks are as follows:

Order number	$p_o^{LeadtimePurchasing}$	$p_o^{programming}$	p_o^{FE}	p_o^w
1	3.5	0.2	0.2	3.5
2	2.5	3	5	5
3	3	5	0.1	5
4	2	2.5	0.4	2.5
5	4	0.1	3	4

Before work preparation is released, work preparation tasks cannot be performed, therefore, the start date of the work preparation of order o is given by:
$S_o^w = \min\{t|X_{ot}^w > 0\} \geq r_o^w$, in which X_{ot}^w indicates the fraction of job J_o^w performed in week t.
In a similar manner, the completion time is indicated. The completion time is given by:
$C_o^w = \max\{t|X_{ot}^w > 0\} \leq d_o^w$, in which d_o^w is the due date of the work preparation of order o. Both S_o^w and C_o^w are variables.
The constraints for S_o^w and C_o^w can be transposed into the following linear constraints:

$$S_o^w \geq \sum_{\tau=1}^{t}(PerformingWP_{ot} - PerformingWP_{o\tau}) + \sum_{\tau=2}^{t}\left(PerformingWP_{o\tau} - \sum_{\gamma=1}^{\tau-1} PerformingWP_{o\gamma}\right) + PerformingWP_{o1}$$

$$S_o^w \geq r_o^w$$

$$C_o^w \geq \sum_{\tau=1}^{t} PerformingWP_{ot}$$

$$C_o^w \leq d_o^w$$

These linear constraints include the binary variable $PerformingWP_{ot}$, which indicates if work preparation tasks of order o are performed in week t or not. If work preparation tasks of order o are performed in week t, the value of $PerformingWP_{ot} = 1$ and otherwise, $PerformingWP_{ot} = 0$. If work preparation tasks of order o are performed in week t, the fraction of work preparation performed in week t of order o is more than 0. Therefore, $PerformingWP_{ot}$ is dependent on the fraction of order o which is scheduled in week t, X_{ot}^w. This dependency can be expressed by the following if-statements:

If $X_{ot}^{w} > 0$, then $PerformingWP_{ot} = 1$;
If $X_{ot}^{w} = 0$, then $PerformingWP_{ot} = 0$.

These if-statements can be transposed into the following linear constraints:
$PerformingWP_{ot} \leq X_{ot}^{w} * 1000$;
$PerformingWP_{ot} \geq X_{ot}^{w}$.

Moreover, the decision variable due date of work preparation of order o is included into constraints for the completion time of work preparation of order o. The due date of work preparation of order o has to be decided by the model, such that the due date of the order will be met. Work preparation tasks should be finished on time, such that succeeding processes, which can only start when the preceding process steps are finished, can be completed before the due date of the order. It is assumed that all production steps are performed in series, as given by the routing, and that previous production step need to be completed before the next production step can start.

Work preparation tasks of most orders should be completed before the first production step can start. However, when orders are later in the pgp process, it may be that improvements are needed for only a part of the process. In that situation, production may start while work preparation tasks are not finished yet and all process steps j which are not preceding processes of the work preparation can already be performed. The first process step for which the work preparation of order o should be completed is indicated by the parameter $FinishWP_o$, in which $FinishWP_o = integer$.

The values of $FinishWP_o$ for orders used in the illustrated example problem are as follows:

Order number	$FinishWP_o$
1	4
2	1
3	3
4	2
5	1

Since work preparation tasks should be finished on time such that the due date of the order can be met, due dates of work preparation are dependent on the due date of the order, the first process step for which work preparation tasks of the order should be finished and the duration of succeeding production steps.
This can be expressed by: $d_o^w \leq d_o - \sum_{j=FinishWP_o}^{N} p_{oj}$, in which p_{oj} is the duration of process step j of order o and d_o is the due date of order o.

Durations of process steps of orders used in the illustrated example problem are as follows:

Order number\process step	1	2	3	4	5
1	0.6	0.4	1.8	0.06	0.8
2	1	0.3	2.4	0.2	0.2
3	2	0.1	1	0.25	0.7
4	0.6	0.25	1.2	1.4	1
5	2	0.45	0.3	0.8	1.8

6.1.4. Due date of orders

For the due date of orders, the demanded delivery date is used if that date is feasible and otherwise the earliest possible date that all actions can be finished is used as due date, since it is desired to deliver the order before the demanded delivery date, but if the sum of the durations of all actions is bigger than the time left until the demanded delivery date it can be justified to the customer that the demanded delivery date is not feasible. In that case, the due date will be moved to the earliest possible date that all actions can be finished. Therefore, the due date of order o can be expressed by:

$d_o = \max\left(DemandedDeliveryDate_o, (r_o^w + ceil[p_o^w, p_o^{LeadtimePurchasing} + \sum_{j=1}^{FinishWP_o} p_{oj}] + round[\sum_{j=FinishWP_o}^{N} p_{oj}]\right)$.

The corresponding demanded delivery dates and due dates of the orders in the illustrated example problem are as follows:

Order number	$DemandedDeliveryDate_o$,	d_o
1	11	11
2	12	13
3	13	13
4	12	12
5	11	12

6.1.5. Process steps

The completion time and start date of production step j of order o can be given in a similar way as for the work preparation. The completion time of production step j of order o can be given by:
$C_{oj} = \max\{t | X_{ojt} > 0\} \leq d_{oj}$, in which X_{ojt} indicates the fraction of job J_{oj} performed in week t and d_{oj} is the due date of process step j of order o.
The start date of production step j of order o can be given by:
$S_{oj} = \min\{t | X_{ojt} > 0\} \geq r_{oj}$, where r_{oj} is a variable, $r_{oj} = integer$ and

$$r_{oj} \geq \begin{cases} C_o^W, \ if\ j = FinishWP_o \\ r_o^W + p_o^{LeadtimePurchasing}, \ if\ j = 1 \\ C_{o(j-1)}, \ if\ j > 1 \end{cases}$$

These constraints can be transposed in the following linear constraints:

$S_{oj} \geq \sum_{\tau=1}^{t}\left(PerformingProcess_{ojt} - PerformingProcess_{oj\tau}\right) + \sum_{\tau=2}^{t}\left(PerformingProcess_{oj\tau} - \sum_{\gamma=1}^{\tau-1} PerformingProcess_{oj\gamma}\right) + PerformingProcess_{oj1}$

$S_{oj} \geq r_{oj}$

$r_{oFinishWP_o} \geq C_o^W$

$r_{o1} \geq r_o^W + p_o^{LeadtimePurchasing}$

$r_{oj} \geq C_{o(j-1)}, \ for\ j > 1$

$C_{oj} \geq \sum_{\tau=1}^{t} PerformingProcess_{ojt}$

$C_{oj} \leq d_{oj}$

Comparable with $PerformingWP_{ot}$, $PerformingProcess_{ojt}$ is used in linear constraints for start and completion times of process steps. $PerformingProcess_{ojt}$ is a binary variable and indicates if process step j of order o is performed in week t. $PerformingProcess_{ojt}$ is dependent on the fraction of process step j of order o planned in week t. This dependency can be expressed by the following if-statements:
If $X_{ojt} > 0$, then $PerformingProcess_{ojt} = 1$;
If $X_{ojt} = 0$, then $PerformingProcess_{ojt} = 0$.

These if-statements can be transposed into the following linear constraints:
$PerformingProcess_{ojt} \leq X_{ojt} * 1000;$
$PerformingProcess_{ojt} \geq X_{ojt}.$

Moreover, the due date of process step j of order o has to be decided by the model in a similar manner as the due date of work preparation tasks. Process steps should be finished on time such that the due date of the order can be met for the process step itself and its succeeding production steps. The due date of process step j of order o is dependent on the due date of the order and durations of succeeding process steps. The due date of process step j of order o can be expressed as: $d_{oj} \leq d_o - \sum_{i=j+1}^{N} p_{oi}\ for\ j > 0.$

6.1.6. Fractions performed and finished

To meet the due date of an order, the order should be delivered before the due date. Before an order can be delivered, each process step j and the work preparation should be finished. Before process steps or work preparation tasks are finished, the sum of the fractions which are planned over the weeks for process steps, or work preparation tasks should be 1. Therefore, the following constraints are included into the model: $\sum_{t=r_o^w}^{d_o} X_{ot}^w = 1$ and $\sum_{t=r_o^w}^{d_o} X_{ojt} = 1$. Moreover, the fraction which is scheduled is always positive. Therefore, $X_{ot}^w \geq 0$ and $X_{ojt} \geq 0$.

Furthermore, the maximum fraction which can be scheduled in a week is dependent on the minimum duration of the work preparation of order o or on the minimum duration of process step j of order o. This dependency can be expressed by $X_{ot}^w \leq {}^1/_{p_o^w}$ and $X_{ojt} \leq {}^1/_{p_{oj}}$.

For orders in which one or more previous process steps ($\alpha < j$) are scheduled in week t, the maximum fraction which can be performed of process step j of that order at week t is decreased, since process step j can only start after all previous process steps are finished. Therefore, the maximum fraction which can be performed of process step j of order o at week t can be expressed by: $X_{ojt} \leq {\left(1 - \sum_{\alpha=1}^{j-1} p_{o\alpha} * X_{o\alpha t}\right)}/{p_{oj}}\quad for\ j > 1.$

Moreover, for process steps for which work preparation is a preceding job, the sum of the scheduled tasks of work preparation and the succeeders of the work preparation tasks in week t, should be smaller or equal than 1 week. This can be expressed by: $p_o^w * X_{ot}^w + \sum_{j=FinishWP_o}^{N} X_{ojt} * p_{oj} \leq 1.$

Furthermore, preceding tasks should be finished before the succeeder can start. Process steps which are succeeders of the work preparation trajectory can only start when work preparation tasks are finished. Process steps which are succeeders of the work preparation have index $j \geq FinishWP_o$. The relation between starting the succeeder and finishing the work preparation trajectory can be expressed by: $PerformingProcess_{ojt} \leq \sum_{\tau=r_o^w}^{t} X_{o\tau}^w\ \ for\ j \geq FinishWP_o.$

For process steps which have index $j > 1$, the relation between starting the process step and finishing the preceding process step can be expressed by: $PerformingProcess_{ojt} \leq \sum_{\tau=r_o^w}^{t} X_{o(j-1)\tau}\ \ for\ j > 1.$ For process step j with index $j = 1$, the process can only start when the purchased materials are available. Therefore, the earliest possible start of the process can be expressed by: $PerformingProcess_{ojt} \leq \left(t - \left(r_o^w + p_o^{LeadtimePurchasing}\right)\right) * 0.001 + 1\ for\ j = 1.$
Moreover, performing work preparation tasks cannot start before the order is released for the work preparation trajectory. This can be expressed by the following constraint: $PerformingWP_{ot} = 0\ for\ t < r_o^w.$

6.1.7. Capacity constraints

Besides meeting due date and fraction constraints, the planning should satisfy capacity constraints. At all times t, the sum of production at resource c for all orders o and production steps j cannot be bigger than the total available capacity of resource c, therefore, the model should contain a constraint like the following constraint: $\sum_{j=1}^{N}\sum_{o=1}^{M} q_{ojc} * X_{ojt} - Q_{ct} \leq 0$, in which q_{ojc} is the required capacity of resource c for order o and production step j and Q_{ct} is the available capacity of resource c at time t.

The available capacity of resources c at all time t of the illustrated example problem is as follows:

Resource c	Available capacity at all time t (Q_{ct})
1	1
2	1
3	1
4	1

In the situation of VDL ETG Almelo, multiple routings are possible with different machines since some proceedings can be performed on multiple machines. Resource c from which capacity is required to perform process step j of order o, which is the machine to which process step j of order o is assigned, is dependent on the chosen routing.

In general, one standard machine is assigned to process step j of order o and other routings which includes another machine can be used as an alternative if capacity is not available at the standard machine. In general, differences between standard and alternative machines are nihil. The reason that a standard machine is selected has to do with predetermined loading. Since machine loading is related to available capacity, the model assumes that the priority of assigning the standard machine, or an alternative machine is equal. Therefore, priorities are not included in the choice for a routing.

Resource c from which capacity is required, with other words, the utilized machine, can be determined by the variable K_{ojc}. K_{ojc} indicates if capacity is required from resource c ($K_{ojc} = 1$) or not ($K_{ojc} = 0$).
K_{ojc} is dependent on variable $Chooserouting_{ojr}$ and parameter $InternRoutingMachine_{ojcr}$.
This dependency can be expressed by the following constraint:
$K_{ojc} = \sum_r Chooserouting_{ojr} * InternRoutingMachine_{ojcr}$.
Moreover, $K_{ojc} = Bin(0,1)$ and $\sum_c K_{ojc} = M_{oj}$, since it is assumed that one process step will be performed at one machine and only in case of performing process step j of order o intern, assigning a resource is required.

The output of the current ERP system which calculates with infinite capacity, indicates the number of hours capacity is required for process step j of order o. In the model, this required capacity is indicated by R_{oj}. From which machine this capacity is required is dependent on which machine is assigned to process step j of order o of the chosen routing.

The required capacity to perform process step j of the orders of the illustrated example problem are as follows:

Order number\process step	1	2	3	4	5
1	1	2	1	2	1
2	2	1	2	1	2
3	2	1	2	1	2
4	2	2	1	2	1
5	2	1	1	1	2

Subsequently, the required capacity of machine c for process step j of order o, can be expressed as $q_{ojc} = K_{ojc} * R_{oj}$, since $q_{ojc} = 0$ if machine c is not chosen and $q_{ojc} = R_{oj}$ if machine c is the assigned resource of the chosen routing. Since K_{ojc} is a variable, q_{ojc} is a variable as well. Moreover, X_{ojt} is also a variable, which results that $\sum_{j=1}^{N} \sum_{o=1}^{M} q_{ojc} * X_{ojt} - Q_{ct} \leq 0$ is a non-linear constraint. Therefore, other constraints are required for considering capacity limitations.

To make sure that capacity limitations are not exceeded, the model includes the variable $CapacityLeft_{ojct}$, which indicates the maximum capacity of resource c which is left at time t after process step j of order o is scheduled. In all cases, $CapacityLeft_{ojct}$ should be positive since capacity levels cannot be negative. Therefore, $CapacityLeft_{ojct} \geq 0$. Moreover, capacity which is left after a process step of an order is scheduled, is always smaller or equal than the total available capacity at resource c at time t. Therefore, $CapacityLeft_{ojct} \leq Q_{ct}$.

The machine, which is utilized, from which capacity is required, is dependent on the chosen routing ($Chooserouting_{ojr}$). The machine which is utilized for process step j of order o is linked to the chosen routing, which is indicated by $InternRoutingMachine_{ojcr}$. The amount of capacity which is utilized for process step j of order o at time t is dependent on the required capacity for performing process step j of order o (R_{oj}) and the fraction of process step j of order o which is scheduled in week t (X_{ojt}). Therefore, $CapacityLeft_{ojct} \leq Q_{ct} * Chooserouting_{ojr} - InternRoutingMachine_{ojcr} * R_{oj} * X_{ojt} + \left(1 - Chooserouting_{ojr}\right) * (R_{oj} + Q_{ct})$.

The capacity, which is left, is not only dependent on the capacity used for process step j of order o, but also dependent on the capacity used by earlier planned process steps. Therefore, for calculating the minimum capacity, which is left, is dependent on the capacity left at time t of resource c after the previous planned process step ($CapacityLeft_{o(j-1)ct}$) instead of the total available capacity of resource c at time t (Q_{ct}). Therefore, the capacity of resource c which is left at time t after process step j of order o is scheduled, should satisfy the following constraints: $CapacityLeft_{ojct} \leq CapacityLeft_{o(j-1)ct} - InternRoutingMachine_{ojcr} * R_{oj} * X_{ojt} + \left(1 - Chooserouting_{ojr}\right) * R_{oj}$ and $CapacityLeft_{ojct} \leq CapacityLeft_{o(j-1)ct}$.

Besides capacity used by earlier planned process steps of the same order, capacity used by earlier planned orders should be considered as well for determining the minimum capacity of resource c which is left at time t after process step j of order o is scheduled. Therefore, the following constraints are included into the model as well: $CapacityLeft_{ojct} \leq CapacityLeft_{(o-1)(jj)ct} - InternRoutingMachine_{ojcr} * R_{oj} * X_{ojt} + \left(1 - Chooserouting_{ojr}\right) * R_{oj}$ and $CapacityLeft_{ojct} \leq CapacityLeft_{(o-1)(jj)ct}$.

6.1.8. The corresponding model

Decision variables of the corresponding model are as follows:

Decision variables	Makes a decision about
M_o	To produce order o intern or outsource order o
M_{oj}	To perform process step j of order o intern or outsource process step j of order o
K_{ojc}	Utilizing machine c for process step j of order o or not
X_{ot}^w	The fraction of the work preparation of order o which will be planned in week t
X_{ojt}	The fraction of process step j of order o which will be planned in week t
d_o^w	The due date for the work preparation trajectory of order o
d_{oj}	The due date for process step j of order o
S_o^w	The start date of the work preparation trajectory of order o
S_{oj}	The start date of process step j of order o
C_o^w	The completion date of the work preparation trajectory of order o
C_{oj}	The completion date of process step j of order o
$Chooserouting_{ojr}$	If routing r will be chosen for process step j of order o
$PerformingWP_{ot}$	To perform work preparation tasks of order o in week t or not
$PerformingProcess_{ojt}$	To perform process step j of order o in week t or not
$CapacityLeft_{ojct}$	The capacity left of machine c at time t after process step j of order o is scheduled

Parameters for this model can be categorized in multiple categories. Input for the model is coming from the ERP system and from estimations. Moreover, some other parameters are calculated from relations with other parameters. In the following table, parameters of the model are given:

Parameters with data from ERP system	Parameters with data from estimations	Parameters which are calculated from relations with other parameters
$CurrentWeek$	$pp_{purchasing}$	p_o^w
$DemandedDeliveryDate_o$	$pp_{programming}$	d_o
p_{oj}	$p_o^{LeadtimePurchasing}$	r_o^w
Q_{ct}	$p_o^{Programming}$	
R_{oj}	p_o^{FE}	
O_{oi}	$maxprocessoutsourcing_o$	
$routingIntern_{ojr}$		
c_{oj}		
$price_i$		
$complexity_i$		
cat_o		
$InternRoutingMachine_{ojcr}$		

Subsequently, the objective of the model is:

$$min \sum_{o=1}^{M}\sum_{j=1}^{N}\sum_{i=1}^{P}((1-M_o)*(O_{oi}*price_i*complexity_i)+\left(M_o-M_{oj}\right)*\left(C_{oj}+\frac{O_{oi}*price_i*complexity_i}{maxprocessoutsourcing_o+1}\right))$$

s.t.

$$M_o \geq 2-cat_o \;\; \forall o$$

$$M_o \leq \frac{3}{cat_o} \;\forall o$$

$$M_o \geq M_{oj} \quad \forall o,j$$

$$M_{oj} = \sum_r routingIntern_{ojr} * Chooserouting_{ojr} \;\; \forall o,j$$

$$\sum_{c=1}^{L} K_{ojc} = M_{oj} \;\; \forall o,j$$

$$maxprocessoutsourcing_o + (1-M_o)*1000 \geq \sum_{j=1}^{N}\left(1-M_{oj}\right) \;\; \forall o$$

$$PerformingWP_{ot} = 0 \; for \; t < r_o^w \; and \; \forall o$$

$$PerformingWP_{ot} \leq X_{ot}^w * 1000 \;\; \forall o,t$$

$$PerformingWP_{ot} \geq X_{ot}^w \;\; \forall o,t$$

$$PerformingProcess_{ojt} \leq X_{ojt} * 1000 \; \forall o,j,t$$

$$PerformingProcess_{ojt} \geq X_{ojt} \;\; \forall o,j,t$$

$$X_{ot}^w \leq {}^{1}\!/_{p_o^w} \;\; \forall o,t$$

$$\sum_{t=r_o^w}^{d_o} X_{ot}^w = 1 \;\; \forall o$$

$$\sum_{t=r_o^w}^{d_o} X_{ojt} = 1 \;\; \forall o,j$$

$$X_{ojt} \leq {}^{1}\!/_{p_{oj}} \;\; \forall o,j$$

$$X_{ojt} \leq {}^{\left(1-\sum_{\alpha=1}^{j-1} p_{o\alpha} * X_{o\alpha t}\right)}\!/_{p_{oj}} \;\; for \; j>1 \;\; and \;\; \forall o,t$$

$$p_o^w * X_{ot}^w + \sum_{j=FinishWP_o}^{N} X_{ojt} * p_{oj} \leq 1 \;\; \forall o,t$$

$$PerformingProcess_{ojt} \leq \sum_{\tau=r_o^w}^{t} X_{o\tau}^w \;\; for \; j \geq FinishWP_o \; and \; \forall o$$

$$PerformingProcess_{ojt} \leq \sum_{\tau=r_o^w}^{t} X_{o(j-1)\tau} \;\; for \; j>1 \; and \; \forall o$$

$$PerformingProcess_{ojt} \leq \left(t-\left(r_o^w + p_o^{LeadtimePurchasing}\right)\right)*0.001+1 \;\; \forall o,j,t$$

$$S_o^w \geq r_o^w \;\; \forall o$$

$$S_o^w \geq \sum_{\tau=1}^{t}(PerformingWP_{ot} - PerformingWP_{o\tau}) + \sum_{\tau=2}^{t}\left(PerformingWP_{o\tau} - \sum_{\gamma=1}^{\tau-1} PerformingWP_{o\gamma}\right) + PerformingWP_{o1} \;\; \forall o$$

$$S_{oj} \geq \sum_{\tau=1}^{t}\left(PerformingProcess_{ojt} - PerformingProcess_{oj\tau}\right) + \sum_{\tau=2}^{t}\left(PerformingProcess_{oj\tau} - \sum_{\gamma=1}^{\tau-1} PerformingProcess_{oj\gamma}\right) + PerformingProcess_{oj1} \;\; \forall o,j$$

$$S_{oj} \leq \sum_{\tau=1}^{t}\left(PerformingProcess_{ojt}\right) + \left(1 - PerformingProcess_{ojt}\right) * 1000$$

$$S_{oj} \geq C_{o(j-1)}, for\ j > 1\ and\ \forall o$$

$$S_{oj} \geq C_o^w for\ j \geq FinishWP_o\ and\ \forall o$$

$$S_{oj} \geq r_o^w + p_o^{LeadtimePurchasing}\ for\ j = 1\ and\ \forall o$$

$$C_o^w \leq d_o^w\ \ \forall o$$

$$C_o^w \geq \sum_{\tau=1}^{t} PerformingWP_{ot}\ \ \forall o$$

$$C_{oj} \geq \sum_{\tau=1}^{t} PerformingProcess_{ojt}\ \ \forall o, j$$

$$C_{oj} \leq d_{oj}\ \ \forall o, j$$

$$d_o^w \leq d_o - \sum_{j=FinishWP_o}^{N} p_{oj}\ \ \forall o$$

$$d_{oj} \leq d_o - \sum_{i=j+1}^{N} p_{oi}\ \ \forall o, j$$

$$\sum_r Chooserouting_{ojr} = 1\ \ \forall o, j$$

$$K_{ojc} = \sum_r Chooserouting_{ojr} * InternRoutingMachine_{ojcr}\ \ \forall o, j, c$$

$$CapacityLeft_{ojct} \leq Q_{ct} * Chooserouting_{ojr} - InternRoutingMachine_{ojcr} * R_{oj} * X_{ojt} + \left(1 - Chooserouting_{ojr}\right) * \left(R_{oj} + Q_{ct}\right) \forall o, j, c, t, r$$

$$CapacityLeft_{ojct} \leq Q_{ct}\ \ \forall o, j, c, t$$

$$CapacityLeft_{ojct} \leq CapacityLeft_{o(j-1)ct} - InternRoutingMachine_{ojcr} * R_{oj} * X_{ojt} + \left(1 - Chooserouting_{ojr}\right) * R_{oj}\ \ for\ j > 1\ and\ \forall o, c, t, r$$

$$CapacityLeft_{ojct} \leq CapacityLeft_{o(j-1)ct}\ \ for\ j > 1\ and\ \forall o, c, t$$

$$CapacityLeft_{ojct} \leq CapacityLeft_{(o-1)(jj)ct} - InternRoutingMachine_{ojcr} * R_{oj} * X_{ojt} + \left(1 - Chooserouting_{ojr}\right) * R_{oj}\ \ for\ o > 1\ and\ \forall j, c, t, r, jj$$

$$CapacityLeft_{ojct} \leq CapacityLeft_{(o-1)(jj)ct}\ for\ o > 1\ and\ \forall j, jj, c, t$$

$$M_o, M_{oj}, K_{ojc}, PerformingWP_{ot}, PerformingProcess_{ojt}, Chooserouting_{ojr} = Bin(0,1)\ \ \ \forall o, j, c, t, r$$

$$X_{ot}^w, X_{ojt}, CapacityLeft_{ojct} \geq 0\ \ \ \forall o, j, t, c$$

$$d_o^w, d_{oj}, S_o^w, S_{oj}, C_o^w, C_{oj} = integer$$

6.1.9. Solution tests

As a result, the following due dates for process steps and the work preparation trajectory are decided by the model for the illustrated example problem:

Ordernumber (o)	Due date order (d_o)	Due date work preparation (d_o^w)	Process step (j)	1	2	3	4	5
1	11	10	Due date process step j (d_{oj})	7	8	10	10	11
2	13	8	Due date process step j (d_{oj})	9	10	12	12	13
3	13	11	Due date process step j (d_{oj})	10	11	12	12	13
4	12	8	Due date process step j (d_{oj})	8	8	9	11	12
5	12	6	Due date process step j (d_{oj})	8	9	9	10	12

To fulfill these due dates, the following starting and completion dates are decided for the illustrated example problem:

Ordernumber (o)	Starting time work preparation (S_o^w)	Completion time work preparation (C_o^w)	Process step (j)	1	2	3	4	5
1	3	10	Starting time process step (S_{oj})	7	7	8	10	10
			Completion time process step (C_{oj})	7	8	10	10	11
2	4	8	Starting time process step (S_{oj})	9	10	10	12	12
			Completion time process step (C_{oj})	9	10	12	12	13
3	4	11	Starting time process step (S_{oj})	7	9	9	11	11
			Completion time process step (C_{oj})	9	9	11	11	13
4	3	8	Starting time process step (S_{oj})	5	6	6	7	9
			Completion time process step (C_{oj})	6	6	7	9	12
5	3	6	Starting time process step (S_{oj})	7	9	9	10	11
			Completion time process step (C_{oj})	8	9	9	10	12

The corresponding weeks in which work preparation tasks are scheduled are given in the table below. These tasks are performed in the weeks between the starting time of the work preparation and the completion time of the work preparation. The week numbers of the starting and completion time of the work preparation are red colored and the weeks in which work preparation tasks are performed are indicated by a 1 and otherwise by 0.

$PerformingWP_{ot}$	Weeknumber (t)	3	4	5	6	7	8	9	10	11
Ordernumber (o)										
1		1	1	0	1	1	0	0	0	0
2		0	1	1	1	1	1	0	0	0
3		0	1	1	1	1	1	0	0	0
4		1	1	1	0	0	0	0	0	0
5		1	1	1	1	0	0	0	0	0

For process steps, the weeks in which process steps are performed are indicated in a similar manner as for work preparation tasks. The weeks in which process steps are performed are indicated by 1 in the following table and the starting and completion times of these process steps are red colored.

$PerformingProcess_{ojt}$	Weeknumber (t)	5	6	7	8	9	10	11	12	13
Order number (o)	Process step (j)									
1	1	0	0	1	0	0	0	0	0	0
	2	0	0	1	1	0	0	0	0	0
	3	0	0	0	1	1	0	0	0	0
	4	0	0	0	0	0	1	0	0	0
	5	0	0	0	0	0	1	0	0	0
2	1	0	0	0	0	1	0	0	0	0
	2	0	0	0	0	0	1	0	0	0
	3	0	0	0	0	0	1	1	1	0
	4	0	0	0	0	0	0	0	1	0
	5	0	0	0	0	0	0	0	1	1
3	1	0	0	1	1	0	0	0	0	0
	2	0	0	0	0	1	0	0	0	0
	3	0	0	0	0	1	1	1	0	0
	4	0	0	0	0	0	0	1	0	0
	5	0	0	0	0	0	0	1	0	1
4	1	1	1	0	0	0	0	0	0	0
	2	0	1	0	0	0	0	0	0	0
	3	0	1	1	0	0	0	0	0	0
	4	0	0	1	1	1	0	0	0	0
	5	0	0	0	0	1	0	1	0	0
5	1	0	0	1	1	0	0	0	0	0
	2	0	0	0	0	1	0	0	0	0
	3	0	0	0	0	1	0	0	0	0
	4	0	0	0	0	0	1	0	0	0
	5	0	0	0	0	0	0	1	1	0

The corresponding fractions of the process steps performed in these weeks are given in the following table, in which the weeks in which actions are performed are green colored.

X_{ojt}	Weeknumber (t)	5	6	7	8	9	10	11	12	13
Order number (o)	Process step (j)									
1	1	0	0	1	0	0	0	0	0	0
	2	0	0	1/2	1/2	0	0	0	0	0
	3	0	0	0	4/9	5/9	0	0	0	0
	4	0	0	0	0	0	1	0	0	0
	5	0	0	0	0	0	1	0	0	0
2	1	0	0	0	0	1	0	0	0	0
	2	0	0	0	0	0	1	0	0	0
	3	0	0	0	0	0	7/24	5/12	7/24	0
	4	0	0	0	0	0	0	0	1	0
	5	0	0	0	0	0	0	0	1/2	1/2
3	1	0	0	1/2	1/2	0	0	0	0	0
	2	0	0	0	0	1	0	0	0	0
	3	0	0	0	0	0.178571429	0.32148571	1/2	0	0
	4	0	0	0	0	0	0	1	0	0
	5	0	0	0	0	0	0	0.357142857	0	0.642857143
4	1	1/2	1/2	0	0	0	0	0	0	0
	2	0	1	0	0	0	0	0	0	0
	3	0	3/8	5/8	0	0	0	0	0	0
	4	0	0	0.178571429	1/2	0.321428571	0	0	0	0
	5	0	0	0	0	11/20	0	9/20	0	0
5	1	0	0	1/2	1/2	0	0	0	0	0
	2	0	0	0	0	1	0	0	0	0
	3	0	0	0	0	1	0	0	0	0
	4	0	0	0	0	0	1	0	0	0
	5	0	0	0	0	0	0	4/9	5/9	0

The corresponding fractions of work preparation tasks performed per week are given in the following table, in which the weeks in which tasks are performed are green colored.

X_{ot}^{w}	Weeknumber (t)	3	4	5	6	7	8	9	10	11
Ordernumber (o)										
1		2/7	1/7	0	2/7	2/7	0	0	0	0
2		0	1/5	1/5	1/5	1/5	1/5	0	0	0
3		0	1/5	1/5	1/5	1/5	1/5	0	0	0
4		1/5	2/5	2/5	0	0	0	0	0	0
5		1/4	1/4	1/4	1/4	0	0	0	0	0

The routings chosen by the model to perform the process steps are indicated by 1 in the following table, in which intern routings are green colored. Not chosen routings are indicated by 0.

The corresponding utilized machines are indicated by 1 in the following table and not utilized machines for process step j of order o are indicated by 0. Process steps for which an outsourcer is assigned instead of a machine are red colored.

$\boldsymbol{Chooserouting_{ojr}}$	Routing (r)	1	2	3	4
Order number (o)	Process step (j)				
1	1	0	1	0	0
	2	0	1	0	0
	3	1	0	0	0
	4	1	0	0	0
	5	1	0	0	0
2	1	0	0	0	1
	2	0	0	1	0
	3	1	0	0	0
	4	1	0	0	0
	5	0	1	0	0
3	1	1	0	0	0
	2	0	1	0	0
	3	0	0	1	0
	4	1	0	0	0
	5	1	0	0	0
4	1	0	1	0	0
	2	1	0	0	0
	3	1	0	0	0
	4	0	1	0	0
	5	1	0	0	0
5	1	1	0	0	0
	2	0	0	1	0
	3	1	0	0	0
	4	1	0	0	0
	5	1	0	0	0

$\boldsymbol{K_{ojc}}$	machine (c)	1	2	3	4
Order number (o)	Process step (j)				
1	1	1	0	0	0
	2	0	0	1	0
	3	0	1	0	0
	4	0	0	0	0
	5	1	0	0	0
2	1	0	0	0	0
	2	0	1	0	0
	3	0	0	0	0
	4	1	0	0	0
	5	0	1	0	0
3	1	0	0	0	0
	2	0	0	1	0
	3	0	0	0	1
	4	0	1	0	0
	5	0	0	0	0
4	1	0	0	1	0
	2	0	0	0	0
	3	0	1	0	0
	4	0	0	0	1
	5	1	0	0	0
5	1	0	0	0	0
	2	0	0	0	0
	3	0	0	0	0
	4	0	0	0	0
	5	0	0	0	0

It is verified that if an intern routing is chosen, the chosen routing is green colored in the table above, that an intern machine is assigned for performing the process step. Otherwise, the chosen routing is not colored, and all machines are not utilized for performing the process step and are red colored.

To verify that green marked chosen routings are performed intern, process steps which are performed intern are indicated by 1 and process steps which are outsourced are indicated by 0 in the following table. Moreover, orders which are at least partly produced intern are indicated by 1 and orders which are fully purchased are indicated by 0 in the table.

Ordernumber (o)	M_o	Process step (j)	1	2	3	4	5
1	1	M_{oj}	1	1	1	0	1
2	1	M_{oj}	0	1	0	1	1
3	1	M_{oj}	0	1	1	1	0
4	1	M_{oj}	1	0	1	1	1
5	0	M_{oj}	0	0	0	0	0

Last, in figure 36 an overview is given of the processes of the orders of the illustrated example problem. The overview gives insight in when work preparation tasks and process steps are scheduled, what preceding relations are between processes and which machine is assigned to perform the process step.

Orders which are purchased and process steps which are outsourced are red colored in the overview of figure 36. Work preparation tasks of orders which are at least partly produced intern are green colored. Machines 1, 2, 3 and 4 utilized for performing processes are respectively colored yellow, blue, orange and pink.

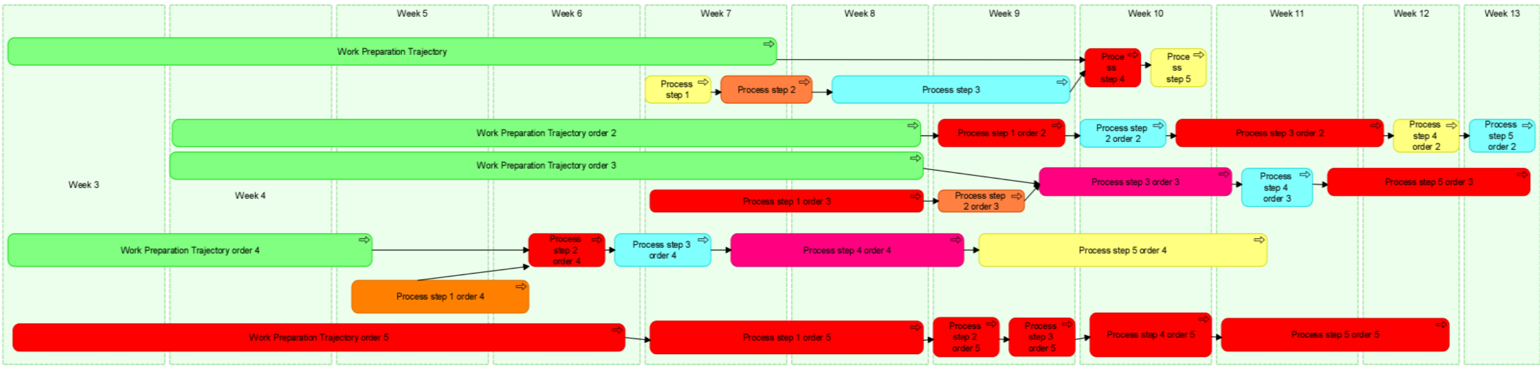

Figure 36. Overview of the schedule for the example orders including assigned machines. Red-colored processes are purchased, or outsourced, green-colored processes are work preparation tasks for orders which are partly produced intern and yellow, blue, orange and pink colored processes are processes which are respectively assigned to machine 1, 2, 3 and 4.

As can be verified from this overview, machines are not double assigned. However, in week 9 machine 4 is assigned to both order 3 and order 4. In week 9, the proceedings of process step 4 of order 4 are finishing, while the proceedings of process step 3 of order 3 are starting. Therefore, the proceedings of order 3 can be performed at machine 4 after the proceedings of order 4 at machine 4 are finished. While for week 10 machine 1 is assigned to both order 1 and order 4, proceedings of order 4 are not scheduled in week 10. Since these proceedings are started in week 9 and will be continued in week 11, the proceedings are given in the overview from week 9 till week 11 to indicate that the proceeding is in progress.

6.2. Model for getting insight into engineering population

In a similar manner as planning orders and deciding what process steps will be outsourced and what will be performed intern, linear programming can be used for getting insight into engineering population. A model for optimizing the optimum number of Factory Engineers and CAM Engineers would be useful for getting insight in required capacity at Factory Engineering and Programming.

Moreover, it would be beneficial to schedule work preparation tasks over the available capacity of Factory Engineering and Programming. Since it is undesirable to have big fluctuations in the number of employees required, it is desired to minimize the fluctuations of engineering capacity required.

For example, if 5 FEs are employed at the department and in week 1, 2 and 4 exactly 5 FEs are needed and in week 3, 9 FEs are needed, it would be more realistic to hire 1 FE for 4 weeks instead of 4 FEs for 1 week. In that situation, it is desired to spread the work such that every week 6 FEs are working.

Decisions made in the model for planning orders and making decisions for outsourcing and performing intern, can be used as input for a model which gives insight into required engineering capacity. Among others, decided due dates for work preparation tasks and release dates for work preparation tasks can be transformed into parameters for such a model. Moreover, the fact if it is decided to purchase or produce a customer order is a relevant parameter to consider in a model for determining required engineering capacity, since intern engineering capacity is not required if the order is purchased.

It is suggested to minimize fluctuations of the number of FEs and CAM engineers required. Therefore, it is suggested to minimize the maximum required capacity of FEs and CAM engineers. Moreover, it is suggested to consider both fractions of engineering tasks scheduled and some buffer time for among others working on older projects, fixing deviations/problems, maintenance activities, improving processes, keeping own processes up to date and initiating tests.

6.3. Model for rescheduling

Besides linear programming for predictive scheduling, in which among others dual source decisions are made and for getting insight into required engineering capacity, linear programming can be used for reactive scheduling. Decisions made by the model for predictive scheduling can be used as input for a model for reactive scheduling. Moreover, input of a model for reactive scheduling may include data about unexpected events, actual durations which deviates from estimated durations and arrival of urgent orders and/or tasks.

To deal with uncertainties and modifications, a model for reactive scheduling would be beneficial, such that earlier made decisions can be considered during rescheduling. While during predictive scheduling the agreed due date needs to be met, during reactive scheduling the agreed due date may not be feasible anymore due to unexpected events and modifications. Therefore, it is suggested that a model for reactive scheduling includes an objective which minimizes (the maximum) lateness.

It is suggested to consider among others data about modifications, decisions made about what process steps are performed intern and due dates from the model for predictive scheduling and consider both machine capacity and engineering capacity as input for a model for reactive scheduling.

6.4. Summary solution design

In this chapter, a linear model is described for making decisions about dual source assignment, machine assignment and schedules. This linear model is based on predictive scheduling. Moreover, suggestions are made for using linear programming for getting insight into required engineering capacity and for reactive scheduling to deal with unexpected events and modifications.

Decisions made by the model for predictive scheduling are among others if processes are performed intern or outsourced and which machines are assigned to intern processes, which are both dependent on machine loading and available machine capacity. Moreover, due dates for work preparation tasks and process steps are determined by the model based on agreed delivery times by the customer. Based on the determined due dates for work preparation tasks and process steps, starting and completion times are decided for these processes. Besides that starting and completion times are related to determined due dates, starting and completion times are dependent on the fractions of the tasks performed per week. The sum of the fractions performed between the starting and the completion time should be 1. Besides that these tasks have to be performed between the starting and the completion time, fractions which can be performed in a week are dependent on process durations and on available machine capacity.

Chapter 7. Conclusions & recommendations

To conclude, this research is done to acquire a comprehensive understanding of the processes of the Parts Manufacturing department of VDL ETG Almelo, such that requirements for the migration to a new ERP system can be drawn and the performance of KPIs can be improved. One of the most important KPIs of the department is the delivery reliability. Therefore, requirements drawn during this research includes both requirements for a new ERP solution which supports intern processes and requirements for improving logistic processes which intend to increase the delivery reliability rate of orders.

The research question this research intended to answer is:
What are the needs of VDL ETG Almelo in order to improve logistic processes and implement a new digital ERP solution such that the delivery reliability rate of orders substantially increases?

To answer this research question, processes are analyzed and shortcomings, drawbacks and desires experienced by stakeholders of the department are investigated by interviewing stakeholders. Based on shortcomings, drawbacks and desires, needs are drawn, and literature research is done to find out what planning methodologies are covered for related processes and needs. Subsequently, planning methodologies covered in literature are used as a basis for designing a model for scheduling and decision-making for dual source assignment, machine assignment for intern production and determining due dates.

During this research a model is designed for decision-making to demonstrate that decision-making can be automized and to suggest how linear programming can be used for decision-making and acquiring insight into scheduling problems. The designed model includes the procedure for dual source assignment used at VDL ETG Almelo, which considers the required technology for determining if a product will be produced intern or purchased, since the company makes use of dual source.

Designing the linear model has contributed to the intersection of practice and theory. Rough Cut Capacity Planning theory from literature has been used as a basis for designing a linear model and is modified by adding decision making procedures from practice. Therefore, the designed model contributes to both practice and theory. Moreover, analyzing processes and finding methodologies suggested by literature for comparable situations have contributed to practice.

Conclusions

After analyzing the processes, it can be concluded that processes at the Parts Manufacturing department of VDL ETG Almelo includes variation in products, the maturity of manufacturing process design of products and uncertainties. Uncertainties include quality issues which may occur, machine failures, unavailable materials, variation in duration of engineering tasks, supply fluctuations and demand fluctuations, may cause schedule disruptions and may have influence on the costs and complexity of managing projects. To eliminate disruption due to quality issues, controlling quality is important. To deal with uncertainties and disruptions during processes, controlling logistic processes is required. It can be concluded that controlling quality, logistic processes and projects are important for managing the department and striving to high performance.

Especially products with a young maturity process design include a variety of uncertainties. These products are projects and require significant effort for engineering tasks. It can be concluded that it is critical for projects to have planning and project management functionalities for resource allocation, schedules and project status monitoring including getting insight into deadlines, deliverables and costs. In project scheduling, it is recommended to consider uncertainties and to eliminate uncertainties by identifying bottlenecks. Besides dealing with uncertainties, it is required to deal with scheduling problems, fluctuating demand and capacity restrictions.

For dealing with capacity restrictions, it can be concluded that capacity planning is required, which is important for decision-making during order acceptance and scheduling. Moreover, it can be concluded that safety stock and dynamic scheduling including a predictive and a reactive mechanism is recommended for dealing with a dynamic environment. It is desired to start with predictive scheduling, in which a baseline schedule is generated to use as a guideline for the project. To react on unexpected events and modifications, reactive scheduling can be used to generate a new schedule or modify the generated schedule.

For creating a baseline schedule, a linear model is designed, which considers dual source restrictions, machine capacity restrictions, precedence relations, possible process routings and due dates for making decisions about dual source assignment, machine assignment and schedules including deadlines for engineering tasks and production processes. Moreover, a suggestion is made how linear programming can be used for getting insight into required engineering capacities including considering decisions made by the model for the baseline schedule, since it is desired to have insight in engineering tasks, including its duration and progress, engineering capacity and engineering workload for projects. Furthermore, a suggestion is made how linear programming can be used for reactive scheduling including considering these modifications and decisions made for the baseline model to deal with unexpected events and modifications.

Limitations and future work

However, suggestions made for getting insight into required engineering capacities and for reactive scheduling for modifying the generated baseline schedule to react on unexpected events and modifications are not validated. These suggestions are just suggestions and are not modeled. The designed model for creating a baseline schedule is modeled and validated by an example problem of 5 orders with each 5 production steps, 4 intern machines and 4 possible production routings containing intern machines and outsourcers, which consist of 3 different products. While the model is working well for such a small example problem, the computability for 1200 to 1500 orders, which is the running number of orders at the department, with more production steps, intern machines and products is not validated.

If the computation time for bigger problems increases significant, it might be more useful to use a simple heuristic instead of linear programming.

For future work, it would be useful to model models for getting insight into required engineering capacities and for reactive scheduling, as suggested. Moreover, it would be useful if the designed model would be validated with real data and bigger samples for getting insight into computation times. Other suggestions for future work regarding models for making scheduling decisions are investigating heuristics, modify the designed model by considering stochastic parameters and expanding the model for including more constraints.

Recommendations

Regarding ERP implementation, it is recommended to investigate impacts of migrating to another ERP system, since migration to another ERP system may have consequences for the processes. Besides investigating impacts, it might be useful to investigate concepts which are discussed in literature to consider during migration. These concepts may include critical success factors for ERP implementation, misfits, risks, barriers and concepts which have impact on the performance of ERP implementation. Moreover, it would be useful to simulate the expected effect of migrating to another ERP system on the performance of KPIs.

Recommendations for implementation include functionalities for project management, managing quality issues, predictive scheduling, reactive scheduling, controlling production flows and analysis. It is recommended to have an integration between production scheduling and control systems including a scheduling module, a controller and a simulation model for detailed capacity planning, simulating consequences of modifications, analyzing plan alternatives and as an input for intern discussions.

For project management, it is recommended to implement a functionality for getting insight into due dates, deliverables, progress and costs. Furthermore, it is recommended to implement a functionality for getting insight into engineering tasks, required engineering capacity and available engineering capacity.

For controlling quality, it is recommended to implement a functionality for getting insight into quality issues and an option for putting products into quarantine. It is desired to get insight into reasons for quality problems, consequences of the quality problems and expected durations for dealing with the quality problems. Moreover, it is desired to have insight into products in quarantine, concession processes, cost of non-quality and expected delay due to quality issues. It is desired to have a Q-list which is insightful, such that it is clear for which orders actions have to be done and which orders are waiting on a decision from the customer about a requested concession.

For controlling production processes, it is recommended to implement functionalities for getting overviews of the progress of processes, machine loading and capacities. Updating intermediate progress and having feedback would be beneficial for having a more up-to-date overview of the progress of processes. It is recommended that the progress of production processes is visual for both logistics and the work floor.

Last, but not least, it is recommended to implement a functionality which makes rescheduling accessible to react on unexpected events and modifications.

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Appendices

Appendix 1. Blueprint

Recommendations for ERP implementation:

- Project planning & project management functionalities:
  - Resource allocation
  - Schedules
  - Project status monitoring
  - Insight into deadlines, deliverables, progress, engineering capacities and costs
- Scheduling, controlling and simulation functionalities:
  - Insight into progress, machine loading and capacities
  - Feedback options
  - Analysis functionalities
  - Functionalities for capacity planning, dynamic scheduling and/or stochastic scheduling
  - Simulation functionalities
- Functionalities for controlling quality issues:
  - Insight into quality issues, reasons & consequences of quality issues, costs of non-quality, expected delay and expected duration of dealing with quality issues
  - Functionality for putting products into quarantine
  - Functionality for controlling products in quarantine and for controlling products in a concession process
- ERP system which includes connect ability with other

Recommendations for process improvement:

- Controlling logistic processes
- Controlling quality
- Considering uncertainties
- Identifying bottlenecks
- Update intermediate progress
- Rescheduling to react on unexpected events and modifications
- Capacity planning, dynamic scheduling and/or stochastic scheduling
- Simulating consequences of decisions
- Digitizing production folders

Roadmap for further research:

- Investigating impacts of migrating to another ERP system
- Investigating critical success factors for ERP implementation
- Investigating misfits, risks and barriers of ERP implementation
- Simulating expected effect of migrating to another ERP system on performance of KPIs

Appendix 2. Questionnaire stakeholder interviews:

All stakeholders:

- Can you give a short description of your tasks?
- To what extent are your tasks order-dependent?
- For the tasks which are order-dependent, to what extent are the tasks the same for each order and/or to what extent are the durations of the tasks constant?
- Are processes and orders at your division/department classified in different groups/types, and/or can it be classified into different groups/types according to you?
  - If so, how can/are processes and orders classified?
  - To what extent are you able to forecast the duration of the process based on the type of order?
- What are the current KPIs at your division/department?
- What are the actual scores on the KPIs and what are the target scores on that KPIs?
- What are the reasons for the gap between the actual scores and the target scores on the KPIs according to you?
- Are these reasons considered as bottlenecks?
  - If so, where are these bottlenecks located, in the ERP system, in the processes are somewhere else?
- How are the scores of the KPIs developed over time?

All stakeholders, except managers of the Parts Manufacturing department and the Supply Chain department

- To what extent does your division experience problems with the planning and delivery?
- To what extent are orders arriving later than planned at your division?
- Does arriving later than planned cause more problems as delivering later according to you?
- To what extent are orders delayed at your division?
- If delay is occurred at your division, what are the most common reasons for delay?
- Are these reasons considered as bottlenecks?
  - If so, where are these bottlenecks located, in the ERP system, in the processes are somewhere else?

Managers of the Parts Manufacturing department and the Supply Chain department

- At what division do you experience most problems with the planning and delivery?
- At what division are most orders delayed?
- If orders are delayed, what are according to you the most common reasons for delay?
- How are the processes organized?
- To what extent can the preparation trajectory be seen as a stage or multiple stages of the whole production process?

All stakeholders

- What do you need to do in the ERP/planning system?
- To what extent do you experience sufficient functions/tools in the current ERP/planning system to perform your tasks?
- To what extent do you experience a lack of functions/tools in your interface of the current ERP/planning system you need to perform your tasks?
- What functions and tools are included in your interface of the current ERP system?

- What do you experience as advantages and disadvantages of the functions and tools which are implemented in your interface of the current ERP system?
- To what extent do you experience unnecessary functions/tools in your interface of the ERP system?
- What works fine for you in the current ERP system and what are the benefits of the current ERP system according to you?
- What problems/shortcomings of the current ERP system do you experience?
- What kind of function/tool which is not implemented in the current ERP system would be a benefit for your processes according to you?
- Do you have any additions to consider during the research?
- What are according to you the most important focus points for this research?
- What further suggestions for improvement which fits in this research do you have?

Managers Parts Manufacturing department and Supply Chain department:

- What division specific information should be gathered?
- What should be the focus of the whole research?

Appendix 3. Results Interviews

Manager Parts Manufacturing department: The manager Parts Manufacturing is responsible for the parts manufacturing. The Parts Manufacturing department produces both mechanical as sheet parts, which are both planning and organizing the manufacturing independent. Controlling the department is done by using the Kranenmodel, which means that controlling the process starts gross and becomes even more refined. When an order is received, it will always be accepted and an investigation of what will be done intern and what will be purchased or outsourced is done. In this investigation, capacity is fixed and if more capacity is required, help of suppliers/subcontractors is needed.

All tasks which have to be performed in producing parts are coded. Based on these codes the expected durations of the tasks which have to be performed are known. From the tasks which have to be performed for producing parts, some tasks are always done intern, some are always outsourced and some tasks are sometimes performed intern and sometimes outsourced. The tasks which are sometimes performed intern and sometimes outsourced, the decision of performing the task intern or outsource it is based on the capacity of the department. The tasks which are always outsourced are outsourced because that tasks require specific specialisms VDL ETG does not have or can be performed somewhere else cheaper. Tasks for complex producible parts and orders with volume flexibility are always performed intern.

Routing inside the department is quite universal, which means that practical all orders follow the following process:

Purchasing materials → operation → benchwork → washing (making fat free) → measuring → surface cleaning → supplying

The process becomes more complex in case of compositions of sheets. In that case parts consist of bills of materials.

While the routing of orders are quite universal, proceedings are order-dependent. For every order the section who should deliver most added value, in other words the section with most proceedings, is the responsible section. The performance of the responsible sections are determined based on the precalculated hours and the recalculated hours. The responsible section for a product is determined based on the product portfolio.

Factory Engineering is pivotal and quality is controlling if the procedures made by factory engineering are complied.

The performance of every production cell is determined by its efficiency, which is calculated by the ratio of precalculated and recalculated durations of tasks. In this way every production step has its own responsibility. However, the result is that the production cells only feel the responsibility of its own task and not for the whole production process. According to the Parts Manufacturing manager, this can be considered as a serious bottleneck.

Especially the more complex products require many steps and the routing is long. This routing is generated by the ERP system. Groups of production steps can be made, but is in conflict with the fact that logistics would like to have an overview of the progress. The conflict is cohesion by groups versus controlling small steps.

The problems are a lack of unity and a lack of insight in long routings.

The performance of the department is determined based on the following indicators: delivering on time, quality, process and costs. For some parts it is easier to comply the requirements than for other parts. In case of quality, details result in rework. Delivery time is dependent of the complexity and stability of production and the length of the whole process chain.

The planning makes use of an integral planning system. In theory, the planning system is reliable. However, planning of assembly and parts manufacturing is quite different, which results in difficulties. It would be easier if the planning of parts manufacturing can be detached from assembly.

Planning systems of extern customers are detached, but in the current ERP system it is not possible intern. As a supplier, the Parts Manufacturing department suffers from being connected with the planning of assembly. Dealing with failure and delay of assembly is not possible. Furthermore, if orders of assembly are pushed forward, it results in backlog for the parts manufacturing department.

Since messing around at the end of the chain by assembly result into a change of due date for the parts manufacturing, which causes problems in the planning of the parts manufacturing department, it is desirable to detach the planning of the parts manufacturing department from the planning of assembly.

If the due date for the parts manufacturing department changes, orders are going in backlog or are not needed soon anymore in the ERP system. These changes cause much effort for the planning.

The desire of the Parts Manufacturing department is that the new ERP system supports making decisions by more visual and simulation tools. It is desired that in the new ERP system overviews of machine loading are visual. In the current ERP system, data is not visible. Therefore, Excel is used for overviews of machine loading. If it is visual what the machine loading is, planning get more flexibilities. Simulation tools are desired to get insight what will happen if something will be changed in the planning. The ERP system should be able to simulate lead times, play around with waiting times and simulating with no hard processing times by using some slack or using dynamic planning. Furthermore, it is desired that the ERP system can deal with scheduling problems. The current ERP system is able to schedule an individual order, but for multiple orders the system plans the orders over each other. Moreover, it is desired to get insight in priorities. Last but not least, it is desired that the new ERP system is not too complex. It is not handy if nobody understands it.

It is desirable that the planning system is able to deal with uncertainties and can give insight how wide or tight planning should be, such that the planning is transparent.

Furthermore, it is desired to have an infrastructure for the planning for work preparation and programming. Especially for new projects, it is desired to have insight in the planning of those sections. Since planning of those sections are different than that of production maps, it should be probably in another system than the ERP system.

Moreover, it is desired that the quality section is able to put products in quarantine in the ERP system. In the current ERP system the status of orders can only be in process or cancelled. In the current situation parts with a deviation are thrown away in the ERP system, while a decision have to be made if the part will be accepted or if rework or scrap is required. At this manner, parts are lost for a while in the ERP system, while it is desired for logistics to have insight in parts who are waiting for a decision. Since waiting for a decision may take long, a new order will be made such that production can start again to prevent the risk of an even longer delay if the part is rejected. If the part with deviation is accepted, the new started part production will be used for an order in the future.

Mechanical manager of the Parts Manufacturing department: The Parts Manufacturing department produces both mechanical and sheet parts. Since the mechanical parts production is bigger than the sheet production, the department has a mechanical manager. The mechanical manager heads the following sections: logistics & planning, Quality Control, work preparation, programming and production. The task of the mechanical manager is to arrange and coordinate the performance of the overall process. The processes includes both new projects and current parts. The phases projects follow are from proto to pilot to volume production. When a project has reached the phase volume production, it is considered as a current part.

One of the main performance indicators of the mechanical manager is efficiency. Efficiency is calculated by the ratio pre-calculation/recalculation. Pre-calculation is done based on a forecast, which is validated and adjusted if needed by a simulation of programming and later on the pre-calculation is adjusted based on the recalculation of the protos. Other important KPIs are machine loading and Confirmed Line Product Performance (CLIP), which indicates the delivery reliability. Since the delivery reliability decreases when the machine loading increases, and the other way around, the main challenge is to find the optimum balance between delivery reliability and machine loading.

Every week the managers and heads of the different sections have a PI weekly flow meeting. In this meeting, the KPIs are reviewed. Besides efficiency, delivery reliability and machine loading, information about backlogs, downtime orders, unmanned hours, orders with a deviation and the anonymous result are reviewed as well.

The number of backlogs, the downtime orders and the orders with a deviation should be controlled to maintain delivery reliability and to prevent lateness. In case of deviation, orders are going in quarantine, since it should be measured if the deviation is allowed or if rework of scrap is required. If the duration of this quarantine is long, it will have a negative result with respect to the lead time of the whole process and thus the delivery reliability.

In case of machine loading, it is useful to know how many unmanned hours are used such that the number of operating hours of the machines can be calculated. However, at this moment it is not insightful what the number of operating hours of machines are, while machine loading is an important KPI. The procedure is the problem in this case. Counting the number of operating hours is done by clocking of the operators, which is not accurate.

For controlling the overall costs, the anonymous result is an important indicator. The expected costs for the projects are based on forecasts. These expected costs are transferred to running projects. The results of the projects are taken anonymous, such that in case of deviation, a project will not increase significant in costs, but the additional costs are divided over multiple projects. The anonymous result should be around 0, such that the actual and the expected costs are cancelling each other out.

The complexity of the processes are that the processes consist multiple process steps. For some orders, some process steps are outsourced or parts are even purchased. The decisions for producing or purchasing parts and performing process steps intern or outsourcing process steps are based on machine loading capacity and the production portfolio. For the process steps which are performed intern, the durations are precalculated. Not a specific process step can be seen as a bottleneck, since it depends on the type of order. For every order actions are the same, but the activities, which determine the amount of work, are variously.

For every order, tasks can be divided into direct and indirect tasks. Direct tasks are production tasks, while indirect tasks are all tasks around it, such as activities of work preparation and programming. For new projects, indirect tasks of work preparation and programming are the bottlenecks. In the proto phase much effort of indirect tasks are required. In the pilot phase still effort of work preparation is required, but this effort is more about keeping an eye on the process. When a project is going from the pilot phase to the volume phase, work preparation transfers the procedures of the project to production and quality control.

Since all sections have to deal with the ERP system, the ERP system should be easy to use and insightful. The current ERP system requires clicking through many tabs. For the new ERP system it would be beneficial if less clicking through tabs is required, it is easier to use and it is more insightful.

The mechanical manager does not use the ERP system itself, but analyses the data which is coming from the ERP system. To analyze this data, the mechanical manager uses icubes. Icubes is an excel interface, which makes use of pivot tables. The drawback of icubes is that printing out icubes is very complex. Therefore, printing icubes is only done during night, with the result that data is lagging behind one day. For the mechanical manager it would be beneficial to have more real-time data. Furthermore, it would be beneficial if data from the ERP system could be transferred as fast as possible into charts to get more insight in the process. This would be beneficial for production as well.

According to the mechanical manager, it is important to investigate how sections are informed by the ERP system about the progress of new orders. Information about tasks which have to be done and when materials or orders are arriving are interesting to know. Do sections receive a splitlist or a trigger when a task should be done or when information about tasks or materials are available?

In the current situation logistics brings a list with important orders to production. Moreover logistics arranges for production that materials are on time available.

Manager Supply Chain department: The supply chain department is a supporting department, which manage the planning of the ERP system and fills in the customer orders and forecast demand. In this manner the demand becomes available for the Parts Manufacturing department. The planning of customer orders are planned by planners of assembly and forecast demand is based on information of the sales department.

Sales has contact with customers and asks for their expected demand. Some customers made a good forecast themselves and for other customers it is more asking for indications. The planning horizon is around 5 quartiles. For some clients, the investigation of the forecast is for longer than 5 quartiles, but orders for more than 5 quartiles in future are not yet put in the ERP system.

The ERP gives for every order when what should be done and what materials are required.

Customer orders are in the system for several months before it has to be finished. Adjoint to the customer orders, forecasts are in the ERP system. When an order is received, a forecast is passed on an order.

Some of the drawbacks of the current ERP system are that the interface is old-dated and for using the system it is required to click into the sessions.

To simplify the ease of use some automation actions are done with separate text-files.

It is desired that the new ERP system is much more equipped with automation and the processes.

VDL ETG has two kind of products, which are flow products and projects. For flow products, forecasts can be made pretty well. Even variation in demand can be investigated. For projects, forecasts can barely be made, since projects are uncertain and often one-off.

Currently, simulations are not done for ERP planning, but simulations for capacity planning are done. Based on the capacities of machines and the expected demand simulations are done in Excel. The available operation hours of machines/machine groups are compared with the expected demand of operation hours. In this manner, mismatches are plotted and insights are obtained what products causes planning problems. Based on this information, decisions can be made if machine capacity should be expanded or what products or process steps should be outsourced by suppliers/subcontractors. Every month an investigation of capacity planning is done by a simulation tool. This investigation shows among others what products are running, what processes are outsourced and what are the differences between capacity demand and available capacity.

Every Monday KPIs are discussed and once in the two weeks this discussion is going deeper. The KPIs are most on operational level. One of the most important KPIs is the delivery reliability, which is dependent on the performance of both sales, assembly and supply, which is from both parts manufacturing and purchasing. If for example parts manufacturing performs low, the planning is not reliable for assembly. Therefore, both an overall delivery reliability and a delivery reliability per supplier is given.

Next to delivery reliability, information about backlogs, actual planning and stock is reviewed as well. For reviewing backlogs, both information of operation hours which are planned in backlog and operation hours planned in the coming weeks are taken into account, since it is dependent on the operation hours planned for the coming weeks if backlog will cause problems. By reviewing the actual planning, it is reviewed if the actual planning includes bottlenecks. By reviewing stock, it is reviewed if bigger, more optimal batch size do not exceed the barriers of having stock. Both on financial and storage area perspectives, stock should be minimized. Especially for products which are rarely sold, stock is not desirable.

The variety of how often systems are sold varies from 4 times per week to once per year. For products which are regular sold, it is more common to go for efficiency. For those products, having stock is not a big problem.

On the other hand, intermediate stocks are beneficial for more stable production and results in less quality problems. However, the problem of imbalance of production is that production will be leveled and intermediate stocks fluctuate.

At the parts manufacturing department larger parts, which are the more important and larger parts to produce, are produced by a stable move rate, such that a stable production plan can be followed. These parts requires much capacity in terms of both machine capacity as storage area and follow a leveled production plan. Unless the stable production, these parts cause much disturbance, since assembly and parts manufacturing are not aligned enough.

The whole trajectory is quite long and the lead times are long. Furthermore, the trajectory includes critical moments with quality issues as well. Occasionally, quality issues arise, which cause delay. For stable production it is important that Parts Manufacturing department supplies a stable amount of parts. While the process is designed for pull production, sometimes push production is used in practice, which causes imbalance.

Because of the long chain, it is not visible what the progress is. If the lead time would be shorter, progress would be more visible. The problem is that progress is not visually visible.

It is desired to get more insight in the progress of the process. It is desirable to have information about which orders are in process and that the workflow is visible. Therefore, a progress monitor is desired. Furthermore, an applied planning system (APS) would be desired as well.

At this moment extracts of the data are used to analyze the performance of the process. Data from the ERP system is not directly analyzed, but intermediate steps are required to make graphics and tables with the use of reporting tools.

It would be useful to connect systems to each other, since an ERP system is not suitable for everything. An ERP system is really useful for keeping control of transactions, but is not suitable for planning. Furthermore, ERP is not suitable for some bottlenecks. Therefore, another system is desired for something like simulations.

An Manufacturing Execution System (MES) is used to digitalize production information.

While ERP stops with the amount of producible parts which have to be planned, a detailed planning is required at the Parts Manufacturing department.

The current ERP system calculates with infinite capacity. By using infinite capacity it is more clear what should be done when, which makes it more visible what bottlenecks are. Since ERP calculates step-by-step, by using finite capacity orders would be postponed at a process step if a machine is already full-loaded. If at multiple process steps orders will be postponed because machines are already full-loaded, the result would be much delay. In that case it would probably more handy to move an order forward in the schedule. However, planning with infinite capacity results in a not feasible planning. Therefore, especially for the Parts Manufacturing department, it is desired to use an Applied Planning System (APS), which makes use of data from the ERP system.

Manager Digitization: Manager Digitization is a quite new position. The manager Digitization arranges the digitization of processes. Currently the company still makes use of much paperwork, which will be transferred into digital information. Until now, automation projects are done by Excel. In the past automation projects were done by Factory Engineers. However, when it is done by Factory Engineers only the viewpoint of the Factory Engineers is taken into account. Therefore, a side position is created, which is the Manager Digitization. The Manager Digitization is working for the whole ETG group in the Netherlands, which means that the Manager Digitization is working for multiple ETG companies.

Since Infor is stopping with the support of Baan this or next year and it is necessary for becoming a digital factory to change to a modern ERP system, the Manager Digitization is working on the transfer to a new ERP system. At this moment a selection is made of three potential ERP packages. The potential ERP packages are InforLN, SAP and VBS. A new ERP package will be selected based on risks and its implementation trajectory. Furthermore, customization is important for the new ERP system, such that it can support the processes best.

To find out what criteria are required for the new ERP system, SAP workshops are organized for employees from multiple departments, Vendor-Managed-Inventory (VMI) is used to figure out what is required from suppliers and klaproos is used. Furthermore, the ERP system should support the process. Therefore, methodologies such as MRP should be implemented.

To become a digital factory it is required to have clear in the system what the routing, the required steps and the end product are and what is required for it.

The bottlenecks of current ERP system are that flexibility is hard, documentation is hard to link, much effort is required for planning by hand and big buckets for planning results in a lack of precision. Furthermore, current ERP system does not send on what should be produced at a certain moment, which results in that operators choose by themselves on what order proceedings will be done.

It is desired to link multiple systems with each other. Systems which should be linked are among others ERP, PLM and MES. ERP is about what have to be made, what the timing is for production and its revision. PLM, which is product lifecycle management, includes product specifications and documentation for the manufacturing of parts/products. MES, which is manufacturing execution system, is the serving hatch for production and includes what skills are required for specific proceedings.

When an order is received, an order number arises in the ERP system. This order number will be linked to an article number and follows the process routing of that article. The proceedings of the process are documented in PLM. From the proceedings documented in PLM, MES checks what skills are required to perform these proceedings. It is desired if ERP, PLM and MES are automatically connected to each other. Furthermore, it would be beneficial if HR systems, which contains the planning of employees and the skills of each employee, could be connected to the other systems as well. The overall plug package of all systems is the Enterprise System (ES).

Next to orders, man hours need to be planned as well. Currently man hours are planned by hand. Since not everybody is able to process everything, skills have to be linked to processes. In HR systems, the skills of employees are noted. Employees should be scheduled to processes for which they are certified for the skills required. Skills are divided in operating a machine skills and product specific skills. If an employee is certified for operating a machine, that certification is unlimited valid, while product specific skills ends when an employee has not produced that specific product for a while.

It is desired that portals of suppliers and technical documentation are linked to the ERP system. Furthermore, it would be beneficial if delivery reports can be linked to the ERP system as well. Documentation contains build-to-print proceedings and customer sketches/models, which contain specifications from the customer. If manufacturing is outsourced, customer sketches/models are forwarded.

Parts and products should be manufactured, such that customer requirements are met. If manufacturing is done intern, proceedings of work preparation have to be followed, but when manufacturing is outsourced, it is not important how it is manufactured, as long as specifications are met.

For every part a High Impact Part (HIP) rating is given. The lower the number of the HIP rating, the stricter specifications are. The HIP rate indicates if a small change is possible. However, in case of quality deviation, a deviation notice should always be given to the customer. The customer should be asked if the part can go through in the process or if rework or scrap is required.

The mean points for the new ERP system are known, but keys have to be implemented. It should be visible where intervening is necessary. Therefore, data is required, which can make this visible. Support from the ERP system is required such that feedback from the workfloor, planning, interruption and alternative routing are visible.

In Baan, buckets of one week are made, which show in what week what should be planned. Since expected lead times are rounded up, the buckets contain much waiting time. Since the buckets contain waiting times, it is easier to meet the planning. However, by reducing waiting times, the process can be made more lean. Waiting times should be minimized and planning should go more in detail. At this moment precision lacks in planning, since orders are planned in big buckets based on capacity. Without planning in detail, it is not visible what the problems are.

ETG precision, another company of VDL ETG, viewed already some ERP packages with scheduling (detailed planning) functions.

For this research it is interesting to investigate what is possible nowadays. For example what exist for sending documentation, e.g. what functions/tools exist to forward 3D models and settings.

In case of new products, the process consist of a long preparation trajectory with uncertainties. Programming tasks are planned out in time. Work preparation makes proceedings, decides what should be measured, what materials should be used and what should meet quality. For production it is interesting to get updates from work preparation if the preparation trajectory is on time, such that production get insight if starting on time is possible or if it is better to start with another order.

For new products/projects, it would be nice if the ERP system have a project focus.

The implementation of the ERP system is dependent on the employees at the company. Therefore it is good to investigate who the key users are, what the key users do and what they need from the ERP system.

At this moment icubes is used for analyses and worklists, however, it is desired that with a new ERP system extern tools are not needed anymore. It would be nice if for projects manhours can be write out. Furthermore, it is desired if everything which is done in Excel can be done in the new ERP system. Moreover, it is desired to get insight in the ERP system what inconveniences are.

Head Logistics & Planning: The head logistics & planning is responsible for planning the production and loading machines from A till Z including the purchasing of materials. The team includes both operational and tactical purchasers. The customers of the Parts Manufacturing department are for around 90 - 95 % intern customers and for 5 – 10 % extern customers. The logistics & planning section is responsible for a high delivery reliability and optimal machine loading at every moment. Therefore, the logistics & planning section have to balance a high delivery reliability with high machine loading.

The most prominent KPIs of logistics & planning are delivery reliability, machine loading and occupied hours. Logistics & planning is together with production responsible for the performance on occupied hours.

Next to order-dependent tasks, logistics works on improvement projects as well. These improvement projects consider mainly optimizing and automation of ERP devices. The company uses the plan-to-win strategy and focuses on capacity. Operational planners focuses most on planning with the current capacity. While tactical planners look half a year to a year forward to forecast what will happen and what will change. For the forecasted orders, it is analyzed what operations have to be done and if production is equipped to perform these operations.

While forecasts fluctuate a bit, the forecasts are pretty precise. From ASML the forecasts are correct for around 80%. Since forecasts are pretty precise, running production flows flexible through the processes, while new projects disturb the process a lot. New projects are coming in between and need to be done fast, which makes it difficult to manage. The company is not equipped for projects. For running projects, it is possible to increase inventory or lead time if necessary, for new projects, it is more difficult. The difficulty for projects is that it is done in between running production.

When a request for a new project is received, there is time and space to arrange capacity for the request, such that if the request becomes a real order, production can start immediately. However, at that moment it is not sure yet if the request becomes an order. When a request becomes an order, often the drawings are not correct and adjustments have to be done. This makes projects more difficult as well.

The processes are a complex system, which sometimes consist of around 20 operations. All operations are dependent on multiple factors. These factors are among others purchasing parts/materials which should be available, tools and machines which should be available, employees who are linked to a machine who need to be capable to produce the specific product and changes in worked hours. If one factor causes a movement in the planning, it has influence on the rest of the planning as well. Furthermore, the chain is very long. The WIP (Work-In-Progress) at the Parts Manufacturing department is around 70 – 80 orders.

Moreover, the process is dependent on extern capacity of outsourcers as well. If machines are full-loaded or have failures/disruptions, delay is occurred in the process. If delay occurs, it is fast known by the supplier. However, the duration of a machine disruption is unknown and hard to forecast. Little flexibility is available in the lead times. Therefore, it is important to have clear what products have to be done first and which later. The performance in delivery reliability of suppliers are measured as well.

In case of failures and disruption intern, it is in the current ERP system not possible to note it. In that situation, the planning is moved by hand. In case of small failures, the own technical service will fix the failure, but in case of big failures, the department is dependent on technicians of the supplier who will fix the failure. In last case, the duration of fixing the failure may be long.

The two big factors which most often cause delay are machine disruption and quality issues. In case of a quality issue, in 5 days a decision about the part have to be made. After these 5 days, the process of the part have to be set in motion again. In total about 2 weeks will be lost in case of quality issues. The ERP system does not take quality issues into account.

Other causes for delay are that somewhere in the process (intern or extern) other orders are taken up instead of the orders which are planned.

Currently planning is done by hand, which results that too much or too little is planned. Because of the irregular planning, Logistics & Planning are picking at hours and are trying to level the production. Another result is that production is producing different than what is planned. Logistics & Planning plans according to forecasted capacity. The forecasting capacity is based on the average number of hours worked in the last 8 weeks. However, production capacity is dependent on the number of employees and production arranges employees to operate. Moreover, targets for machine loading are given by management which should be taken into account as well.

The process in the ERP system is as follows: for new projects advices are filled by factory engineering and flow products have already a routing into the ERP system and logistics & planning converts orders into a planning. Furthermore, if needed logistics & planning reschedule orders. Logistics & Planning arranges the production planning of the order, the purchasing of materials and the routing of operations which have to be done. Logistics & Planning controls the production order an releases orders. Furthermore, Logistics & Planning communicates with production about production lists for machines, delivery dates and the amount of work. In the current ERP system, production can not give feedback directly.

Suppliers confirm if due dates will be realized, but own production cells do not. It would be a good addition if production cells will confirm if they will realize the due dates.

The main shortcoming of the current ERP system is that clicking through the system is required for using the system. Furthermore, overviews are not included in the ERP system and the ERP system lacks interaction and feedback options. The current ERP system is cumbersome in use and is difficult to use for seldom using users. The current ERP system requires that users are used to the system. It is desired that the new ERP system is user friendly for all users, gives clear overviews and is furnished for automation.

Furthermore, it is desired to have a function which gives insight in what is still in process of a specific product. It should be insightful for all sections, who (which employee) is working on what order, what orders have delay and where are adjustments needed. For example for the Quality Control it would be beneficial to know when what measuring program should be prepared. Overall it is important that the status of orders and who is working on what order is insightful. At this moment, this kind of information is kept up in Excel files, but it is desired to have it in the ERP system.

It is desired that different schedules can be connected to the ERP system. Also tool management is desired to be connected to the ERP system. In the current situation, molds are registered in the ERP system, but it is not registered when it is used, when it is available and when maintenance is required.

Another product/tool which would be nice if it could be registered in the ERP system are packages. At this moment packages are requested by a Kanban system. It would be beneficial if the ERP system would give a trigger when a package is required. It is desired that the new ERP system registers packages and gives a trigger if a package is needed.

Furthermore, standard tools are used at multiple machines/process steps. Especially at milling operations, many different tools are used. It would be nice if these tools are registered in the ERP system as well.

It is desired that the new ERP system can be connected to other systems, such as soflex, dual source (this is an important system which indicate what amount should be produced intern and what amount will be outsourced to what supplier), teamcenter, HR systems, purchasing portals and supplier portals.

Furthermore, it is desired that drawings and documentation such as proceedings can be downloaded from the ERP system by production/process cells themselves. At this moment a paper with proceeding is given. It is desired that this will be digitalized.

The company lags behind digitization, since much paper is used at the moment.

Head Factory Engineering: The head Factory Engineering is the manager of the Factory Engineers, which are actually project leaders. Factory Engineers arrange the manufacturing processes and prepare work proceedings for the manufacturing processes. The work proceedings are prepared in SolidWorks. Customers are cost competitive and demand for a short development trajectory. Factory Engineers accompany customers in designing products and arrange the manufacturing process. Meanwhile, Quality Control request for quality requirements. Moreover, the planning of the manufacturing process has to be aligned with Planning & Logistics.

Much customers ask for advice about manufacturability of new projects. Those products are not yet ripe for production. In that case, VDL ETG joints halfway through the concept phase, which is the business case/first phase of the product generation process. The product generation process describes what happens.

After the concept phase, the project industrializes, which is called the design phase. When the design is finalized, a test sample is manufactured. This phase is called proto. Based on the results of the test sample, adjustments are done and production is challenged by a pilot phase. If the results of the pilot phase are approved, volume production can start. The goal is to work as fast as possible through the phases and approve the drawings. The proto and pilot phases are shortened if possible. Therefore, outsourcers are engaged soon.

The idea is that parts are produced in sequence, which means that parts will be produced again, since customers are staying for a longer period customer of the company. When a project/part will be manufactured for the first time, much effort of Factory Engineers is required, while when the company is already known with the part, effort of Factory Engineers is not required anymore. In case of flow products, Quality Control controls what happens at the process.

Both the proto and the pilot phase consist of two parts. The first part of the proto phase is work preparation, which includes what will be manufactured, what control program is required, what materials are required and what outsourcer can do a coating if needed. The second part of the proto phase are production and measuring the parts which are produced. Based on the measurements of the parts produced in the proto phase, experience is gained. This knowledge/experience is processed as input in the pilot phase, such that production can be improved the next time. After adjusting the feedback points, production will start again.

The pilot phase may take multiple production sets, since the process is still in the pilot phase until production meet the requirements of volume production. If multiple loops are needed, every production set is improved compared to the previous production set. Moreover, the adjustments made for every new loop become even smaller, since the proceedings convert to the final phase. Sometimes it takes 2 years before production is ready for volume production. The duration of the pilot phase is dependent on the order/part. On average the pilot phase has a duration of between 8 and 16 weeks. However, the duration of the pilot phase is dependent of the lead time of a part as well. Some parts have a lead time of 6 weeks while other parts have lead time of 22 weeks.

The duration of the proto phase is forecasted roughly by rounding off by week, while for the pilot phase forecasting can be done more precise based on the actual duration of the proto phase. For the roughly estimation of the duration in the proto phase, some production steps are taken together if one of the steps takes only one day. For example washing and measuring.

Two different planning tools are used at the work preparation section. For projects which are clear, Excel is used to make a Gannt chart, while for complex projects MS projects is used. MS projects is capable to give information about critical resources, critical process routings and control/check points. The planning of the work preparation section is not connected to the ERP, but it is taken over in the planning. According to the head Work Preparation it is not possible to connect the planning of Work Preparation to the ERP system, since the amount of work preparation is unpredictable and according to him ERP works on quite precise estimations. Therefore, the forecasts of work preparation are not exact enough for connecting to an ERP system.

According to the head work preparation, keeping updating the ERP system is waste. Therefore, in the current situation Excel is used to report the progress and this progress is communicated. The goal of reporting the progress is to check if Factory Engineers are on time, why FE are not on time and what FE need.

The desires of the head Work Preparation are to get insight in the costs and in the reasons for delays. In Excel already dumps are build, but the organization is struggling with it. For the reason of delays, it is desired to know what product has delay and if the delay is structural. For the costs, it would give more insight if costs over time are known. Furthermore, feedback of the system is desired. If something is done in the system, it would be beneficial to know what the result/effect will be. In this case mistakes can be eliminated. Moreover, it would be beneficial if the ERP system is more conveniently equipped. The current ERP system is not easy to use. A procedure is required for employees to make use of the current system if employees does not use the ERP system dailies.

The Factory Engineers prepares routings for the processes. It is desired if tools can be put in the ERP by a link between teamcenter and the ERP system. Tools are created in teamcenter and are connected by documentation. In the current ERP system, tools can be added, but not linked to a specific process step. In teamcenter, databases, control programs and tools are awarded to process steps. Furthermore, it is desired that the new ERP system can do something with documentation.

For production it would be beneficial if the ERP shows the planning, at what machine should be produced and what tools are required. During production 3 types of tools are used, namely clamping jigs, bites and carts. Clamping jigs are reported in the current ERP system, but bites and carts are not reported in the ERP system. Therefore, the availability of clamping jigs is known, but for bites and carts not. Bites are needed at the end of milling machines. For some operations even 40 different bites are required. Since these bites are not reported in the ERP system, it is not known what the availability of the bites and what its costs are. For carts it is not insightful where they are when they are needed. Carts are a kind of lost, while they are large.

If an alternative routing is used, insights in chances for improvement can be gained. If a process step is outsourced, the part is still managed by VDL ETG, while operation is done extern. Therefore, quality documents have to be delivered to gain control insight of what can be expected.

Work Preparation does not have hard KPIs. Sometimes it is analyzed for what parts are materials ordered, while the orders of that parts are not released. In that case, it is analyzed what the time is between arrival an releasing. However, at the Work Preparation section it is not controlled based on these durations, because a reason is behind it. The structure at the Work Preparation section is that it constant in backlog, such that it will be picked up directly.

Head Programming: According to the head Programming, VDL ETG is fused with Baan and it is time that the company get up to date. Not only the ERP system is outdated, but the labor division is from that time as well. At this moment logistics controls the status of the processes, such that the responsibility at workfloor is lower. Logistics give oral updates to production. However, it is desired to have an overview of the status for production. A more direct contact between multiple production steps is desired. Communication from process step to process step is desired. Furthermore, it is desired if information of previous process steps is prepared in the ERP system, such that information is available for operations and collecting that information is not only possible by own initiative.

Currently, information is updated during night. However, it is not sufficient to have information once a day. More actual information is desired. Receiving updates every hour should be sufficient. Moreover, data in order portfolio are analysed by Excel files. Multiple Excel files are tied together and since last year icubes is used for reporting.

It is desired to have an overview about the planning integral. Operators should get insight about previous production steps by the ERP system. It is beneficial if previous proceedings supply delivering dates.

It is desired if the preparation trajectory would be integrated with the delivery date. Currently, CAM engineers book their own hours for orders, which is based on an estimation after the scope of the order is discussed with the factory engineer. The time booked for programming is dependent on the order. Small orders can be done in 1 week, while big orders can take half a year. It would be beneficial to have an overview of the booked hours. At this moment, the booked hours for programming are not known by production. Moreover, it is not visible for production what the progress of programming is. The head programming asked for an interface in the ERP in which booked hours could be registered, but it was hard or expensive to get such an interface. Without such an interface, it is difficult to justify hours. It is desired that data of booked hours are available for everybody.

Next to the drawbacks of the current ERP system and the processes, problems in Teamcenter are experienced as well. However, it is not possible to solve these problems by a new ERP system.

The factory engineer prepares folders for programming. Programming works in these files and cut these up in multiple blocks, such that milestones can be controlled. Programming for preparation work, operations and verification are done in separate blocks.

The performance on efficiency of programming is determined by the ratio of recalculation divided by pre-calculation, which means the real number of hours used by programming versus the booked hours by programming.

Next to programming for new projects, programming works on maintenance of machines and improvements of processes as well. If a problem occurs, programming will help fixing the problem. Next to maintaining and improving the programming of machines, programming keeps their own processes up as well. Moreover, programming initiates tests to record production knowledge and to get to know the control of new machines.

Machines are connected to the system soflex. When an order is received at a machine, soflex will be used to check if the order is at the correct machine, what program should be done to manufacture the order and if the required materials are available. When the process step at the machine is done, the duration of the operation is fed back to the ERP system.

The input of soflex is thus when an production order will be received and the output should be the operating durations and the status of an operation. Another input for soflex is the tool database, which is teamcenter. Teamcenter consist data of proceedings and what materials are required.

Furthermore, it is desired to have a button which can be used in case of quality disruption to indicate that probably delay will be occurred.

According to head Programming, it is needed to define a process for quality issues with deadlines such that it is clear what has to be done in 48 hours and what in 2 weeks. According to head Programming, KPIs are needed to control the performance of delivery reliability in case of quality issues.

It is desired to have clear insight in KPIs. It is desired that the new ERP system would be capable to manage resources. It would be beneficial if molds and lifting equipment could be requested in the ERP system, such that it is visible in the ERP system if molds and lifting equipment are available or lent. Furthermore, it would be beneficial if a trigger can be given by the ERP system when maintenance for molds and lifting equipment are required. Moreover, it would be beneficial if the ERP system manage data of when molds and lifting equipment are verified. In the current situation, molds and lifting equipment are not equipped on maintenance and availability. For machines, technical service manage maintenance. For maintenance management, technical service uses its own system.

It is desired that teamcenter will be connected to the ERP system, such that production folders are digital. Currently, much paper work is used in the factory. For maintaining and controlling of production folders it is easier if it is digital, since in a digital environment a list of folders can be selected and adjusting files should be easier. In a digital environment it is possible to do adjustments for both separate files and all files at the same time. It is desired to have a gradually transition from a paper factory into a digital factory.

Furthermore, it is desired to have insight in what costs belong to an order, especially in case of quality issues. If a product fails and other products of that order can continue the process, reporting is 3 months later. In that case, too much hours, disapproval or costs for the whole product are listed. It is desired to get more grip on it and make decision processes more direct and shorter. First an estimation is made, later a final decision.

It is desired that the ERP system is insightful and easy to use. Moreover, it is desired to have an overview who is working on what order. Furthermore, it is desired that products which are in quarantine because of quality issues can be monitored in the process without order, such that performance of products which are in quarantine can be measured and analyzed.

Head Quality Control: Quality Control handles complaints. Complaints are coming from both intern and extern, since the process of some parts are done both at the company itself and multiple outsourcers. If complaints are from intern, a failure in the process is reported by the Quality Control. Complaints are reported in CAQ REM. Parts which are red colored in CAQ REM are in quarantine. Products in quarantine means that it consist a disapproval.

In the current situation, Quality Control makes use of both CAQ REM and the ERP system (Baan). While complaints are controlled in CAQ REM, are logistic processes controlled in Baan. If an failure is reported, the production order and the process step are given. In Baan, the localization of orders registered in a production folder such that it is known at what the progress is of an order. When a failure is reported, the order is indicated by 1 in the control list. Orders indicated by 1 are orders which are in quarantine.

In the current situation folders are scanned weekly, which are registered in an Excel file. In that way, Quality Control can focus on the failures. Failures can be divided in 3 groups, namely small deviation, disapproval (big deviation) and repairable. For repairable products, a recovery strategy is required. If rework is required, it should be discussed with Logistics.

If a complaint arrives, it is reported in CAQ REM. Consequently, the part order in which a failure is found is going in quarantine and stock of the same product and more parts of that product in the chain are checked for failures. Based on the complaint and the result of the check of other parts in the chain, it is analyzed if actions are required. Before actions for recovery will be done, concessions are redelivered to the customer, since the recovery strategy should be approved or even discussed by the customer. Consequently, rework and recovery actions are planned in consultation with logistics. Furthermore, an additional step will be added in case of recovery, namely a QE check, which is an intermediate check. Moreover, if rework is inserted in the process routing, the operation is stamped in the folder and the 1, which indicates that action is required, is replaced by 999.

It is seen as a problem that Quality Control is working too long on parts which are in quarantine. However, the specifications are that hard that parts may or may not meet the specifications. In that way, some products arrives almost always in quarantine. While these products stick to the standard, requesting concession is required. This results in much work and delay. According to the head Quality Control, or specifications or proceedings should be adjusted for these products.

If an order is splitting, it is called a misklip.

In the current situation, concession is not visible in the ERP system. It is desired that it is possible to follow the concession process in the new ERP system, such that it is easy and fast to follow the logistics of an concession. In case of failure, after the failure is observed, the failure is reported and a new routing is designed. After a new routing for recovery is designed, contact is needed and it is required to follow the concession process. At this moment insight in concession lacks and concession takes long. Therefore, concession is often seen as the bottleneck. If much products are in quarantine, a capacity problem arises at the Quality Control section. In that situation, capacity is seen as a bottleneck as well.

To prevent failures, Quality Control checks documentation of purchased products before delivery. Quality Control receive the documentation 5 days before delivery. At this moment, the need for checking documentation is taken over from mail to iQbs by hand. It is desired to have a function for checking documentation in the new ERP system. Since Zeiss is a customer, checking documentation is even more important. Therefore, the company is also more explicit working on intermediate checks.

The focus points of the company are QLTC , which stands for quality, logistics, technics and costs.

For new projects, a FAI development traject is used. In the FAI development traject, assessment time is taken into account.

Work Preparation makes a routing for new products, which is called the product-generation process (pgp). There are pgp requirements for different products. The phases of the product generation process are as follows: concept, design, proto, proto, pilot and volume. Until the pilot phase, work preparation is responsible for the quality and improving it. In the volume phase Quality Control works on it. In the first phases, direction is given in manufacturing steps, later on in the proto and pilot phases, the focus is on stable production and in the volume phase on volume production.

According to the head Quality Control, time should be granted for preparation. According to the head Quality Control, the current ERP system lacks the phases. Measuring is important at manufacturing. The head Quality Control desires to have insight in when and which checks have to be done before an order is going to programming or other sections. At this moment it is not insightful and a lot of contact with work preparation is required. Currently Quality Control receives orders for checks just before orders are going to the production floor. In this way, Quality Control can not plan the work for checking documents. It is desired to be able to plan document checks.

The main KPI of Quality Control is minimize/eliminate customer complaints. This KPI is calculated by the number of complaints from assembly and customers over the total number of supplied parts. The value of this KPI may not be higher than 0.05 %, which is currently not met. Other indicators which are reported are cost of non-quality, outstanding actions and rejects, both intern, supplier and the total. Cost of non-quality signify that if quality issues are reported, Quality Control has to put effort, work and time in that order, which costs money.

The main bottleneck at Quality Control is the duration of concession. Sometimes a specific strategy causes delay in the process.

Head Quality Control: At this moment, the Quality Control consist of 1 section. 2 sections will be added soon. 3 measuring machines are in the Quality Control to measure the parts. If a part is good, the process will be continued, while if a part contains a deviation, the part is going in quarantine. Moreover, the Quality Control checks parts which are going to an outsourcer before it is send to the outsourcer. This action is called meco.

The main tasks of the Quality Control are reporting operations as finished and putting parts in quarantine.

In general, the Quality Control just checks important sizes. However, for new projects, the measuring program has to be programmed by the Quality Control as well. Other projects for the Quality Control are calibration and checking measuring materials.

In the current situation all orders are sent by the ERP system and printed. The Quality Control intends to plan as much as possible, but it is hard to plan with the information given by the ERP system. It is hard that dates are mixed up, both due dates of orders which are already received at the Quality Control and orders which are not available yet are given.

It is desired to have an overview of what orders are received by the Quality Control and what the corresponding due dates are. If a part is disapproved, it is mutated and the operation stays open in the ERP system. It is desired if a part is going in quarantine that it is not in the list of the Quality Control anymore. Furthermore, it is desired that programming the preparation trajectory is more plannable. It is desired to plan from preparing until completion. Moreover, it is a bottleneck that not all outsourcing orders are printed yet, since the list is running behind one day, because it is only updated once a day. It is desired to create the outsourcing orders by themselves. It is desired to follow the orders per hour. In the current situation that is not possible. It is beneficial to have an overview of what operations are available, what operations are not released yet and what operations are in backlog.

The KPIs of the Quality Control are lead time, delivery reliability, the ratio recalculation/pre-calculation and backlog. The difficulty is that parts which are in quarantine are in the ERP system still at the Quality Control. Therefore, the lead time and backlog of parts which have to go in quarantine is not representable for the performance of the Quality Control.

Heads Production: Production is the section which perform direct tasks.

When an order is received from Logistics, first material delivery in own warehouse is done. In the warehouse a warehouse management system (WMS) is used. Other factors which are considered in the process are settings, use of tools and measuring (Quality Control). For some parts, the production process contain 20 operations, while for other parts only 5 operations are needed. Also, the number of operating cells where operations have to be performed fluctuates. For some parts, operations are done at only one operating cell, while for other parts operations are performed at 5 different operating cells. For all parts a machining operation is done.

Other differences between parts are that some parts are standard and a computer controlled program is used for automation of the process, while the performance of the production of other parts are dependent of multiple factors. The lead time of standard parts can be forecasted well, while for other parts, much variability exist in the production process. For these parts, factors such as which operator performed the operation and the existence of additional operations have influence on the lead time.

In the past, stock was registered in the ERP system, but nowadays for most products the stock is registered in the WMS. However, in the current situation, not all products are clear transferred from the ERP system to the WMS.

It is desired that the new ERP system is connected to the WMS.

In the current situation management of the warehouse is a grey area. Logistics knows what is going on, while production controls the warehouse.

For production it is most important to control hours to have insight in costs. Currently, hours are controlled by clocking in of employees. Clocking in hours is done in Orgatime, which is a system for hours.

It is desired to have something else for clocking hours, which is accurate and is correctable. Moreover, it is desired that a tracking document of orders gives a clear overview.

The interface of the heads production is quite limited. The function of head production in the ERP system is coach. One of the tasks of the head production is accounting for hours. This can be done by requesting data about hours in the ERP system and correct data if necessary. Furthermore, reporting operations as complete if this is not done by the operator is a task of the head production as well.

For production it is important to have an overview of hours exceeding and performance of pre-calculation/recalculation of hours, that data for analyzing KPIs is callable and that all operators can do their tasks.

In the current situation, data is analyzed by iQbs.

A bottleneck in the current system is that some operations remain open in the system. This is the issue when previous production steps are not reported as complete. In case of quality issues, the Quality Control does not report the order as complete. In this way, it is not insightful what has to be done, which results that operators choose by themselves which order will be operated first. Furthermore, getting insight in the current planning is cumbersome. In the current ERP system, following orders is not insightful. It is not clearly visible what is finished and what not. Another drawback is that the lists are not up to date. Another drawback is that for new parts it is not known what tools are required and when.

In the current situation, tools which are required are communicated by Excel files and by a briefing given by Logistics.

The current ERP system gives dumps of schedules. Parts which have a long lead time are planned over multiple weeks. Moreover, the current ERP system schedules some parts over multiple weeks for only a couple of hours per week, which is not optimal. In the current situation, the planning is controlled by Excel. In that manner, the planning is quite up to date, every 20 minutes an update is done.

It is desired to have as production some influence on the output. It is desired to have an overview of precalculation and recalculation. Moreover, it is desired to have a suitable function for the workfloor, such that operators have an overview of their own planning. Next to an overview of their own planning, it is desired that operators have insight in hours and who did what. Furthermore, it is desired that the performance of KPIs can be retrieved fast.

KPIs of Production are pre/recalculation, the worked hours of the department and per operation, the number of hours clocked, the number of hours reported as finished, the difference between the number of hours clocked and the number of hours reported and the number of indirect hours of operators. The clocksystem is leading at Production.

According to the heads production delay is occurred when production is on hold because of quality issues, if packing material is not available and if the production process contain large backlogs.

A microplanning is used for planning. The microplanning shows the planning of parts which have to be finished before the end of the week, such that machines can be optimally utilized. It is desired that soflex and the ERP system are linked to each other. In the current situation, Soflex extracts data from Baan and checks when processes have to be done and if everything is available. Soflex is a robot control system. It is desired that the ERP system can read soflex. Information of Baan is going in one dump into Soflex. However, if the planning changes in Baan, nothing is changed in Soflex. It is desired if changes in the ERP system are automatically taken over in Soflex. Otherwise, it is needed to replan by hand.

Heads Purchasing: For Purchasing VDL ETG in Almelo has one Purchase manager. Furthermore, all Purchasers are divided over departments. The heads Purchasing at the Parts Manufacturing department (also called Mechanics, since it is actual the own machine factory of the department) are Strategic Purchasers. The Parts Manufacturing department is the supplier of the assembly department. In total 6 Purchasers, from which 2 strategic purchasers, 3 operational purchasers and one supportive purchaser, are working at the Parts Manufacturing department.

The heads Purchasing, Strategic Purchasers, are responsible for arranging outsourcers for purchasing parts if the production in the factory itself is overloaded. Furthermore, the heads Purchasing determine the policy of the department. The heads Purchasing are responsible for preparing a purchasing plan, set the purchasing plan and improve it. Furthermore, the heads Purchasing select suppliers and are in this way support of the operational purchasers. Purchasing is done for both materials and orders. Project purchasers do the purchasing of orders, while operational purchasers purchase materials. In this manner, purchasing is a bit supply chain furnishing. Moreover, Strategic Purchasers are helping the other purchasers if somewhere help is needed.

The Strategic Purchasers of Mechanics are responsible for setting up, rolling out and implementing the Purchase plan/policy for the department. The operational purchasers are responsible for placing orders and having contact with the suppliers about costs and technical aspects. The supportive purchaser is responsible for controlling order confirmations and the pursuit of orders which are not on time. The Strategic Purchasers collaborate closely with the Planning & Logistics section. Tactical and Operational purchasers are even covered by the Planning & Logistics section.

In case of projects, tasks of Strategic and Operational purchasers have overlap. Controlling orders of new projects is one of the tasks of the Strategic Purchasers, while controlling orders is a task of Operational Purchasers as well. In the proto and pilot phases of a project, the order flow is controlled by Strategic Purchasers. When the production process runs, controlling the order flow is taken over by operational purchasers.

Activities which have to be done in the ERP system by the Strategic Purchasers are adding materials of new projects into the ERP system and extract data from the ERP system for analyses.

The current ERP system, Baan, is powerful, customized and is equipped for adjustments. The current ERP system is working well, however, it is not userfriendly. To make it easier to use, many tools are built around it during the years, such as iQbs and tools for doing forecasts.

However, improvement of the ERP system is possible for several factors. It is desired to have a function to forecast one year forward and to have a function for parts which have deviation. Parts which have deviation are currently reported in the system CAQ, but it is desired that this is reported in the ERP system as well. Furthermore, it is desired to have some automation in the system. It is desired that the supply date is put automatically in the ERP system, that material documents are linked to an order and the correct process step and that measuring reporting demand is automatically generated with supplying a packing list for the measurements. Currently, supply dates have to be inserted by hand into the ERP system.

Moreover, it is desired to have a report with price changes based on a PC/NC analysis. In the current situation, PC/NC analysis is only done on project level and not at purchasing level. Therefore, getting insight into price changes is very complex in the current situation.

In the current situation, twice a week orders are place by operational purchasers. It is desired if this can be changed in once a week. However, urgent adjustments of work preparation are the bottleneck.

In the current situation once a week the planning is adjusted.

It is desired that parts which are not produced for two years are not seen as current parts.

The Parts Manufacturing department of VDL ETG makes use of dual source, since the department outsources the production of parts or operation processes of the production of parts and the department has own production. Purchasing has close interaction with Logistics and in consultation of both Logistics and Purchasing, it is determined what will be produced intern and what will be outsourced. Minimum a certain percentage of total demand should go to outsourcers, as is agreed with outsourcers. It is desired that the minimum percentage which should go to outsourcers is visible in the ERP system and what outsourcers already got. It is desired to get a trigger for the percentage and a trigger when something is changed in the planning.

Performance at the department is controlled by 5 indicators, namely QLTCR, which stands for quality, logistics, technics, costs and risks. The indicators quality and logistics are seen as the most important indicators. To control quality, complaints are always discussed and it is determined what complaints are relevant. With respect to logistics, the CLIP is measured, which indicates in what extent do suppliers keep agreements. KPIs of outsourcers are delivery reliability and quality performance and KPIs for the purchasing plan are delivery reliability and the reject rate. Currently, KPIs are analyzed by sheets which are built around the ERP system in Excel. These KPI sheets, which make use of iQbs, are more visible is more visible for analyzing the KPIs than the ERP system. However, it is desired that KPIs can be analyzed from data in the ERP system. In the current situation CLIP information from the ERP system is given in an overview in iQbs.

Orders which are not confirmed in a week are coming in a list, such that it can be pursued. The current ERP system generates automatically mails. However, these mails are neglected by suppliers.

When a project starts it is required to know if the company has sufficient provision. Therefore, an exposure profile is used in the ERP system. For purchasing materials it is desired that suppliers confirm the supply date. For outsourcing, it is more desired to agree fixed lead times, such that the supply date is already confirmed by creating the order. Nowadays, fixed lead times are agreed with 12 suppliers, however, it is desired to agree this with all outsourcers. Orders are confirmed in the portal sharepoint environment, a purchase portal, which is connected to Baan. Information of the ERP system is printed to the portal. When information of the ERP system is printed to the portal, it is submitted for approval to managers, since for new projects approval of managers is required. Till €250000 approval of the manager of the Parts Manufacturing department is required. Above that amount, approval of the overall manager of VDL ETG Almelo is needed. It is desired that approval is automatically sent/forwarded.

Orders are sent for confirmation to suppliers in two different ways. The first option is by generating a pdf which is sent by mail to the supplier. The mail address which is given in the ERP is used to send the pdf to the supplier. For this option work by hand is required. The other option is by a supplier login environment. If the supplier can confirm it, the supplier receives an email to check it. For most suppliers, the second option is used, since nothing has to be done by hand. However, this option is only used for supplier who are in contact with VDL ETG weekly. When an order is confirmed, it is checked if the supply date corresponds with the due date, if problems will occur and what can be done.

It is desired to have visible what orders will become later in the ERP system. Backlogs are kept up, however, only something is done with it if the supply date should be adjusted.

The process is equipped for production parts in batches.

For new projects, a First Article Inspection (FAI) is done. If an product is new or not produced for more than a year, a FAI notification is given by the ERP system. When a FAI notification is given, advices have to be put into the system and a measuring report have to be delivered.

Baan gives advices for orders. Baan is based on producing of batches. For new parts first information has to be inserted into the ERP system. When information is not complete, for example the supplier, the lead time or the price is missing, advices are not released.

Orders which are not released, but materials or parts need to be ordered by a supplier for that orders, are given a not released code, which is 60100. For these orders, information is not known by the ERP system. Operational purchasers take on these orders, search for the missing information and order the required materials or parts. If a supplier is missing, the supplier, a suitable supplier will be found.

Planned advises from the ERP system are mutated into a planning.

The head logistics approves what can be ordered. After approval, purchasing orders are created for all orders which are released. Baan puts automatically all materials and parts of one supplier on one purchasing order.

For ASML, the orders are anonymous controlled. For these products, a certain number of products has to be produced in one year. Therefore, these products are controlled on expected demand. These products are divided over time in optimal batch sizes.

It is desired to fill own machines for 100% and make use of outsourcers for fluctuations.

In the current situation, 3 actions have to be done for planning orders, namely MRP, PRP and MPS. For MRP and MPS, the ERP system gives anonymous advices. For MRP, these advices are converted into production of purchasing orders and for MPS manual steering is required. On the other hand, for projects advices are not complete. For these orders, PRP orders, are revision adjustments not released and is discussion required.

In the system CoPQ, disruptions and rejection at the outsourcer/supplier are reported. Every night a dump of this information is coming in iQbs from CAQ REM. In iQbs data from CAQ REM and Baan are taken together.

A shortcoming of the current ERP system is that many screens have to be used together if data from the ERP system would be analyzed. In the current situation it is easier to use iQbs for analyses.

The interface of the Strategic Purchasers in the ERP system contain functions for creating and managing purchasing orders, product management (Purchase Procurement), maintaining supplier data, doing adjustments and managing contracts.

In PLM information of anonymous orders are reported. This information contain price information. Prices for different batch sizes can be seen in staffels under the product name.

Another shortcoming of the current ERP system is that inserting information have to be done by hand. If something is copy-pasted, Baan does not know all characters, with a result that adjustments have to be done by hand as well.

Advices given by the ERP system take into account batch sizes and staffelprices. For some products are ordering in certain batch sizes cheaper, while for other products the price is not dependent on the size of an order. In general, lower prices can be demanded when agreements for purchasing per year are made. In that case one purchase price can be agreed independent of what will be ordered when. This is called a contract price.

It is desired that the new ERP system is able to work with 3 kind of prices, namely basic prices, staffelprices and contract prices.

Work Preparation creates the routing in the ERP system. In the current system this is done by hand. It is desired that this will be handier as well. In the current situation some tools are made such that data from Excel can be uploaded into the ERP system. By eliminating inserting data by hand, the chance to make errors are reduced.

Into the interface of the Purchasers, a list with invoice differences is generated. At the moment that a product is received, a packing slip is received by the ERP system. The value of the product should agree with the packing slip. Otherwise, the order is coming on a differences list, which will be received by all operational purchasers. In the current situation 4 or 5 screens are required to check what is not true, which takes a lot of effort. Orders which are on the differences list are blocked for the further process. Therefore, it is important that fixing the errors is done soon.

Logistics fills the dual source quantities, so what will be produced intern and what will be outsourced. However, if production is outsourced by 3 different suppliers, the current ERP system just divides the orders over the suppliers without taking into account minimum batch sizes. It is desired that the new ERP system will divide orders over suppliers by taking optimal batch sizes into account.

Forecasting is important. With 12 suppliers fixed lead times are agreed. These process steps of suppliers with fixed lead times can be put in the ERP system. It is desired to have an actual overview of what orders outsourcers have and what they can expect. Furthermore, it is desired to have an overview when orders will be given to suppliers and when it should be received back. It is desired that the new ERP system is capable to extract expectations for outsourcers.

Appendix 4. Equations for suggested models

In this appendix equations for suggested models are represented. However, these models are not validated.

Suggestions for model for getting insight into engineering population

To make sure that fluctuations of the number of FEs and CAM engineers required are minimized, a model is built in which the maximum required capacity of FE and Programming is minimized. The corresponding objective is: $\min \max_{t=1\ldots T} Q_{FE,t} + Q_{Programming,t}$, in which $Q_{FE,t}$ is the required number of Factory Engineers in week t and $Q_{Programming,t}$ is the required number of CAM engineers in week t. Since only a whole number of employees can be employed, $Q_{FE,t}, Q_{Programming,t} = integer$.

As a result from the model which is used for deciding if an order and/or process steps will be outsourced or manufactured intern, M_o, r_{ow} and d_{ow} are input values for the model which determines the number of FEs and CAM engineers needed. Therefore, M_o, r_{ow} and d_{ow} are parameters in this model.

The number of Factory Engineers can be expressed as: $Q_{FE,t} \geq \sum_{o=1}^{M} p_{oFE} * X_{oFEt} * (1 + buffer_{FE})$, where p_{oFE} indicates the duration of the tasks of Factory Engineering for order o, X_{oFEt} indicates the fraction of the tasks of Factory Engineering of order o planned in week t and $buffer_{FE}$ indicates the buffer of Factory Engineering. The buffer of Factory Engineering is used for among others working on older projects and fixing failures/deviations during the production process.

In a similar way, the number of CAM engineers can be expressed, which is as follows: $Q_{Programming,t} \geq \sum_{o=1}^{M} p_{oProgramming} * X_{oProgrammingt} * (1 + buffer_{Programming})$, where $p_{oProgramming}$ indicates the duration of Programming tasks for order o, $X_{oProgrammingt}$ indicates the fraction of the Programming tasks of order o which are planned in week t and $buffer_{Programming}$ indicates the buffer of Programming. The buffer of Programming is used for among others, maintenance of machines, improvements of processes, fixing problems, keeping own processes up to date and initiating tests.

The fraction of Programming tasks and tasks of Factory Engineering cannot be bigger than the inverse of the minimal duration of respectively Programming tasks and tasks of Factory Engineering, which can be expressed as: $X_{oProgrammingt} \leq {}^{1}/{p_{oProgramming}}$ and $X_{oFEt} \leq {}^{1}/{p_{oFE}}$. Moreover, the tasks of Programming and Factory Engineering of order o should be completely done in between the release date and the due date of the work preparation trajectory of order o if it is decided to produce order o intern. Therefore, the following constraints are included in the model: $\sum_{t=r_{ow}}^{d_{ow}} X_{oFEt} = M_o$ and $\sum_{t=r_{ow}}^{d_{ow}} X_{oProgrammingt} = M_o$. Furthermore, the fraction of the tasks of order o which will be done in week t should be at least 0, therefore, $X_{oProgrammingt}, X_{oFEt} \geq 0$.

The decision variables of this model are as follows:

Decision variable	Makes a decision about
$\boldsymbol{Q_{FE,t}}$	The number of FEs which are needed at week t
$\boldsymbol{Q_{Programming,t}}$	The number of CAM engineers needed at week t
$\boldsymbol{X_{oProgrammingt}}$	The fraction of programming tasks planned in week t
$\boldsymbol{X_{oFEt}}$	The fraction of tasks of FE planned in week t

The parameters of this model can be categorized in in 2 categories, namely parameters from the model which decides what orders to produce and what orders to outsource and parameters for which estimations are made beforehand. The parameters are shown in the following table:

Parameters for which estimations are made	Parameters from the model which decides what orders to produce and what orders to outsource
$\boldsymbol{buffer_{FE}}$	M_o
$\boldsymbol{buffer_{Programming}}$	d_{ow}
$\boldsymbol{p_{oProgramming}}$	r_{ow}
$\boldsymbol{p_{oFE}}$	

The corresponding suggested model may be as follows:

$$\min \max_{t=1\ldots T} Q_{FE,t} + Q_{Programming,t}$$

s.t.

$$Q_{FE,t} \geq \sum_{o=1}^{M} p_{oFE} * X_{oFEt} * (1 + buffer_{FE})$$

$$Q_{Programming,t} \geq \sum_{o=1}^{M} p_{oProgramming} * X_{oProgrammingt} * (1 + buffer_{Programming})$$

$$X_{oProgrammingt} \leq {}^{1}/p_{oProgramming}$$

$$X_{oFEt} \leq {}^{1}/p_{oFE}$$

$$\sum_{t=r_{ow}}^{d_{ow}} X_{oFEt} = M_o$$

$$\sum_{t=r_{ow}}^{d_{ow}} X_{oProgrammingt} = M_o$$

$$X_{oProgrammingt}, X_{oFEt} \geq 0$$

$$Q_{FE,t}, Q_{Programming,t} = integer$$

Suggestions for model for rescheduling

After it is decided to produce intern, modifications in the processes may result in delay, since the capacity of resources is fixed. Therefore, for rescheduling a resource-driven RCCP is suggested, from which the objective is to minimize the maximum lateness, which is given by: $\min \max_{o=1\ldots M} (C_{oj} - d_{oj})$

The input of the rescheduling model includes various parameters which are coming from multiple sources, namely the ERP system, the model for deciding which orders to produce and which orders to outsource and the model for deciding the number of FEs and CAM engineers needed. The parameters, which are the input of the rescheduling model are listed in the following table:

Parameters from the ERP system	Parameters for which beforehand an estimation should be made	Parameters from the model which decides what orders to produce and what orders to outsource	Parameters from the model which decides the optimum number of FEs and CAM engineers
$\boldsymbol{F_{oj}}$	p_{oFE}	r_{ow}	Q_{FEt}
$\boldsymbol{f_{oj}}$	$p_{oProgramming}$	M_{oj}	$Q_{Programmingt}$
$\boldsymbol{p_{oj}}$	Q_{kt}	M_o	
$\boldsymbol{p_{oLeadtimePurchasing}}$		d_{oj}	
$\boldsymbol{A_{ojck}}$			
$\boldsymbol{R_{ojk}}$			

The decision variables of this model are listed in the following table:

Decision variable	Indication of variable
$\boldsymbol{X_{ojt}}$	The fraction of process step of order o which will be performed in week t
$\boldsymbol{X_{oFEt}}$	The fraction of the tasks of Factory Engineering which will be performed in week t

$X_{oProgrammingt}$	The fraction of Programming tasks which will be performed in week t
K_{ojc}	The decision if machine c will be used for process step j of order o or not

The corresponding constraints for this model are:

$\sum_{t=r_{oj}}^{T} X_{ojt} = M_{oj} \;\; \forall o, j$

$\sum_{t=r_{ow}}^{T} X_{oFEt} = M_o \;\; \forall o$

$\sum_{t=r_{ow}}^{T} X_{oProgrammingt} = M_o \;\; \forall o$

$X_{ojt} \leq {}^{1}/{p_{oj}} \quad \forall \, o, j, t$

$X_{oFEt} \leq {}^{1}/{p_{oFE}} \quad \forall \, o, t$

$X_{oProgrammingt} \leq {}^{1}/{p_{oProgramming}} \quad \forall \, o, t$

$$X_{ojt} = 0 \;\; if \begin{cases} \sum_{\tau=r_{o(j-1)}}^{t-1} X_{o(j-1)\tau} < 1 \; for \; j > 1 \\ \sum_{\tau=r_{ow}}^{t-1} X_{ow\tau} < 1 \; for \; j = 1 \end{cases}$$

$$X_{owt} = \begin{cases} \frac{1}{3} * \left(X_{oFEt} + X_{oProgrammingt} + \frac{1}{p_{oLeadtimePurchasing}}\right) for \; t \leq r_{ow} + p_{oLeadtimePurchasing} \\ \frac{1}{3} * \left(X_{oFEt} + X_{oProgrammingt}\right) for \; t > r_{ow} + p_{oLeadtimePurchasing} \end{cases}$$

$\sum_{j=1}^{N} \sum_{o=1}^{M} q_{ojk} * X_{ojt} - Q_{kt} \leq 0 \quad \forall \, k, t$

$q_{ojc} = A_{ojck} * K_{ojc} * R_{ojk} \;\; \forall o, j, \text{c}$

$\sum_{c=1}^{L} K_{ojc} = 1 \;\; \forall o, j$

$\sum_{c=1}^{L} A_{ojck} * K_{ojc} * q_{ojc} = R_{ojk} \;\; \forall o, j, k$

$\sum_{o=1}^{M} p_{oFE} * X_{oFEt} - Q_{FEt} \leq 0 \quad \forall \, t$

$\sum_{o=1}^{M} p_{oProgramming} * X_{oProgrammingt} - Q_{Programmingt} \leq 0 \quad \forall \, t$

$X_{ojt} \geq 0 \;\; \forall o, j, t$

$X_{owt} \geq 0 \;\; \forall o, t$

$C_{oj} = \begin{cases} \max\{t | X_{ojt} > 0\}, \; if \; F_{oj} = 0 \\ f_{oj}, \;\; if \; F_{oj} = 1 \end{cases}$, in which F_{oj} indicates if process step j of order o is reported as finished and f_{oj} indicates week t in which process step j of order o is finished.
Moreover, $F_{oj} = Bin(0,1)$ and $f_{oj} = integer$.

$C_{ow} = \begin{cases} \max\{t | X_{owt} > 0\}, if \; F_{ow} = 0 \\ f_{ow}, \;\; if \; F_{ow} = 1 \end{cases}$, in which F_{ow} indicates if the work preparation trajectory of order o is reported as finished and f_{ow} indicates week t in which the work preparation trajectory of order o is finished.
Moreover, $F_{ow} = Bin(0,1)$ and $f_{ow} = integer$.

$S_{oj} = \min\{t | X_{ojt} > 0\} \geq r_{oj}$

$S_{ow} = \min\{t | X_{owt} > 0\} \geq r_{ow}$, in which r_{ow} is a known parameter from the time-driven model.

$$r_{oj} = \begin{cases} C_{ow}, if\ j = 1 \\ C_{o(j-1)}, if\ j > 1 \end{cases}$$

Appendix 5. Conflicting factors

Besides drawbacks of the current ERP system and the processes, the ERP system and processes are partly in conflict with requirements of the business. These conflicts are as follows:

- The delivery reliability is low, because delivery is regularly not met on time, while delivery reliability is one of the most important KPIs of the department.
- No trigger is given by the ERP system when capacity is exceeded, since the ERP system works with infinite capacity, while capacity is limited.
- The ERP system makes no distinction between project orders and flow products orders, while the processes are quite different.
- The preparation trajectory is not visible in the ERP system, while the preparation trajectory is an important part of the processes of project. Moreover, currently, insight into actions and deadlines of the preparation trajectory lacks.
- While the business is driven on continuous planning, updates with regard to planning are only updated during night into Excel.
- A detailed planning is required at the Parts Manufacturing department, while current ERP system only indicates the amount of producible parts which have to be planned.

Appendix 6. Process overview orders