MASTER

A supply chain planning framework to support the design of master planning processes

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A supply chain planning framework to support the design of master planning processes

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Abstract

Master planning is an instance of supply chain planning and generates the due dates of planned work orders based on the route, capacity, material availability and sales plan (Wiers & de Kok, 2017). Master planning is currently insufficient at the manufacturing company Prodrive Technologies because material coordination and load planning are neglected. This causes too much work and too much inventory. This thesis presents an integrated supply chain planning framework that supports the design of master planning processes at Prodrive Technologies using a constrained-based planning logic and an Advanced Planning and Scheduling system. A comprehensive and structured overview of the master planning process and related processes remains to a large extent unaddressed in literature. Since Prodrive Technologies can be classified as an A-Plant company according to the V-A-T classification by Umble (1992), it is expected that the supply chain planning framework can be applied to other companies characterized by convergent assembly points throughout the production process.

Keywords: master planning processes, supply chain planning framework, MRP, constrained-based planning, material availability, APS

Management Summary

Introduction

This thesis presents a constrained-based master planning process at Prodrive Technologies using an integrated supply chain planning framework. Master planning generates the due dates of planned work orders based on the route, capacity, material availability and sales plan (Wiers & de Kok, 2017). Master planning at Prodrive Technologies is currently insufficient as material and capacity availability are not taken into account. The following management problem is identified: *The master planning process at Prodrive Technologies is ineffective, causing too much work and too much inventory.* In order to implement a master planning logic that takes capacity and material availability into account, an Advanced Planning and Scheduling system for master planning is required as an Enterprise Resource Planning system only provides limited support. The new Advanced Planning and Scheduling system, with master planning that creates a material and capacity feasible plan, should improve the work center output, the make-span of products, the stock level, the Confirmed Line Item Performance and Requested Line Item Performance on production and sales orders and the number of planners required to make a production plan. In order to successfully implement master planning using an Advanced Planning and Scheduling system, the related processes and procedures need to be defined and managed (Rudberg & Cederborg, 2011). Prodrive Technologies also indicates that a structured and comprehensive overview of master planning processes is required in order to implement master planning. Therefore, this research aims to solve the master planning problem of Prodrive Technologies. The main question answered in this thesis is: *How can the design of master planning processes using an Advanced Planning and Scheduling system be supported by a supply chain planning framework at Prodrive Technologies?* This thesis aims to contribute to literature. Therefore, the following research gap is identified: *A comprehensive and structured overview of the master planning processes remains to a large extent unaddressed in literature, even though this is crucial for the successful implementation of the master planning Advanced Planning and Scheduling module.*

Design of SCP framework

Figure 1 presents a new integrated framework that shows all the functions that must be part of supply chain planning according to literature. The grey (sub-)processes are currently not executed at Prodrive Technologies, which confirms that master planning is currently insufficient for Prodrive Technologies as both load planning and material coordination are not present. This also shows that the MRP-II framework misses crucial functions related to master planning. Prodrive Technologies currently uses MRP-I to generate planned work orders. The MRP-I logic is compared to a material feasible logic to get a better understanding of the importance of material coordination.

Material coordination

In the case study, Item B2 is assembled from item B1 and item B1 is assembled from item A. The lead times of items B2, B1 and A are 1, 2 and 4 respectively. The "MAP" column of Table 1 shows the supply and demand plan for each item obtained using the MAP algorithm described by de Kok et al. (2005). The "MRP" column shows the supply and demand plan created using MRP-I for each item. For item B2 in "MAP", the cumulative unconstrained demand is equal to the cumulative demand as it is an end item. For this item, the cumulative supply shows what can be supplied from the preceding item B1. Using the MAP method, the cumulative supply catches up with demand after 7 periods (lead times of item B2, item B1 and item A combined). For the

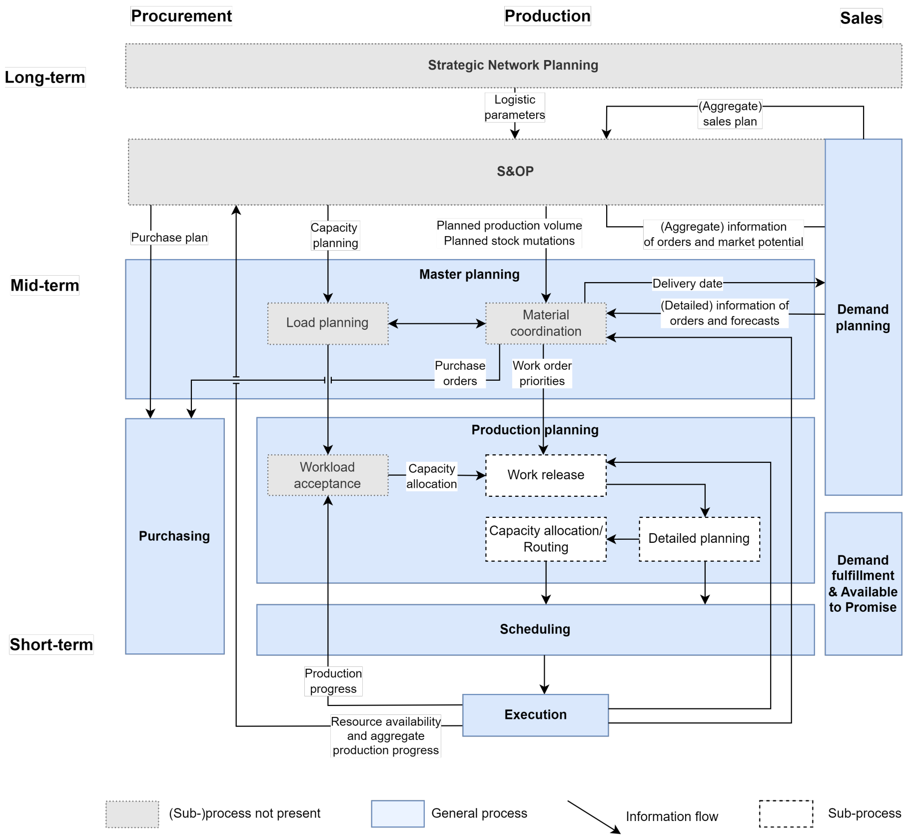
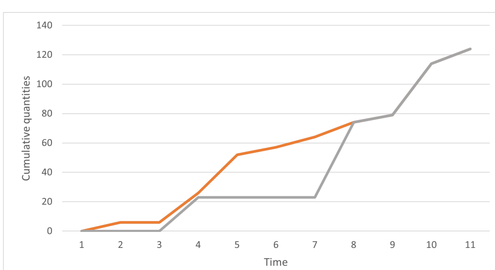
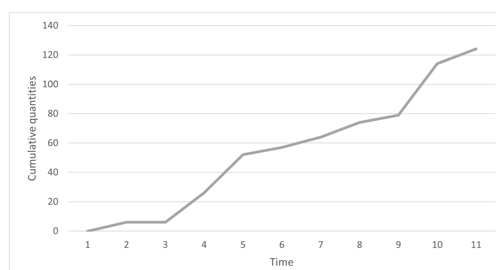
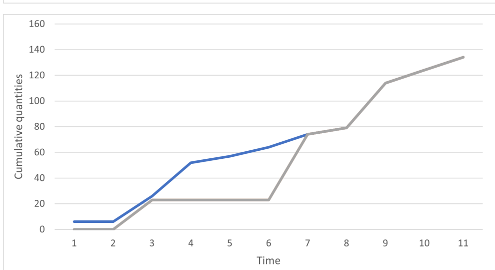
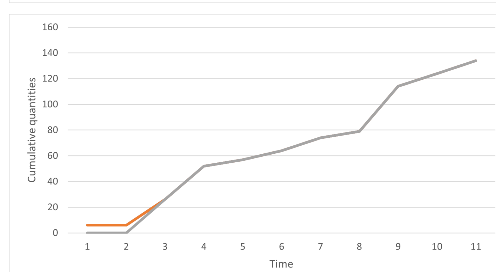


Figure 1: Integrated SCP framework applied at Prodrive Technologies

MRP-I method, it seems as if there are no shortages for item B2 even though this cannot be realized given the shortages of items B1 and A. MAP does show the shortages at end item level. Therefore, this case study shows that the MAP plan is feasible and the MRP-I plan is not.

Item	MAP	MRP
Item B2		
Item B1		

Item A

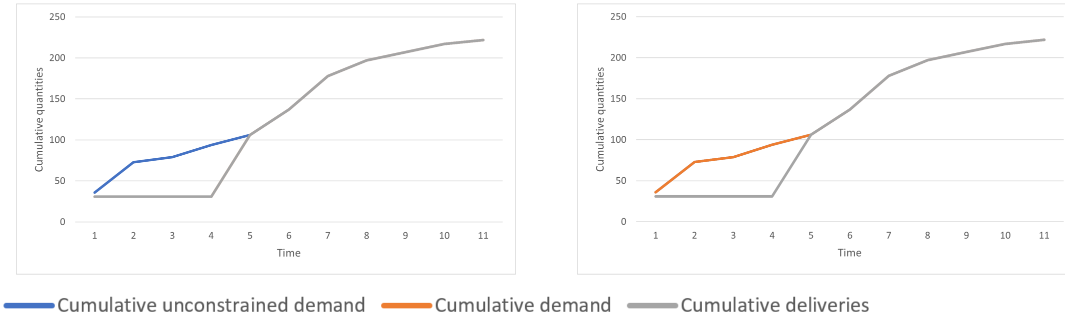


Table 1: Supply and demand plan using MAP and MRP at Prodrive Technologies

Design master planning processes

The proposed master planning processes include a constrained-based planning logic in order to solve the problems identified at Prodrive Technologies. This eliminates the processes where the planning and purchasing department are solving infeasible planned orders at all Bill of Material levels. The proposed master planning processes consist of solving a backlog at MPS level and checking firmed planned orders. It is important to avoid firming an order as firmed orders will not be adjusted by the system and can be infeasible.

Conclusion

The final supply chain planning framework after evaluation is presented in Figure 2. The framework is valuable to gain an overview and structure the processes at Prodrive Technologies based on the face validation of the main stakeholders at Prodrive Technologies. Since Prodrive Technologies is an A-plant category according to the V-A-T classification described by Umble (1992), the framework can be applied to other companies characterized by convergent assembly points throughout the production process. Furthermore, Prodrive Technologies works according to common concepts such as SAP as ERP system. This indicates that the framework is widely applicable.

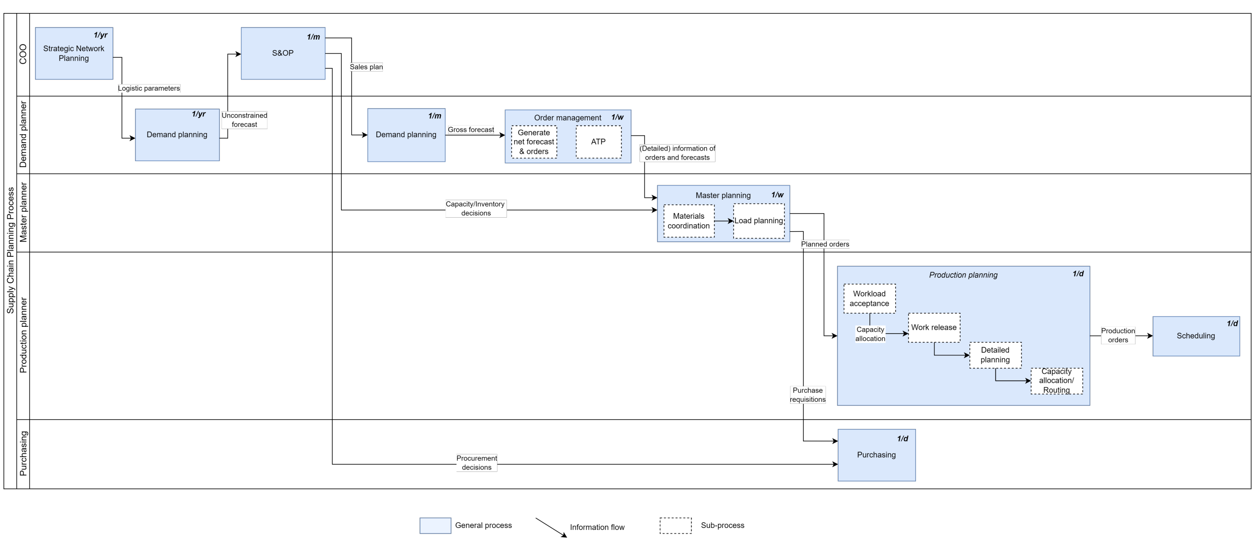


Figure 2: Final swimlane SCP framework

Preface

I proudly present my master thesis, which is part of the master Operations Management & Logistics at the Eindhoven University of Technology (TU/e). I enjoyed working on my graduation project at Prodrive Technologies for the past eight months. This thesis concludes my master and my five years as a student at the TU/e. Therefore, I consider this project a milestone in my academic career. I would like to use the Preface to thank several people.

First of all, I would like to thank my first university supervisor, Irene Vanderfeesten. Our meetings were very motivating and I really enjoyed working with you. Your ideas challenged and inspired me to think out of the box. I truly appreciate how you kept me involved in the SHOP4CF project team and made my thesis more than writing a report. I would also like to thank my second supervisor, Ton de Kok. I find it unfortunate that our collaboration will end after this graduation project as I am convinced that I can learn much more from you. Your passion and expertise is impressive and I am thankful that you shared a part of that with me.

My graduation project would not have been possible without Prodrive Technologies. I would like to thank my first company supervisor Jamie van den Meijdenberg. Thank you for sharing your knowledge and making the time to help me. I truly enjoyed our weekly meetings and many conversations. I would also like to thank Leon de Wit for the interesting discussions and for sharing your expertise. Thank you Pepijn Jansen, together with Jamie and Leon you made office S3.06 my favorite office for the past eight months. Furthermore, I would also like to thank Mike de Beer for giving me the opportunity to conduct my graduation project at Prodrive Technologies. Thank you Alexander Wessel, Bram Linders and Alem Camo for your feedback and time.

Finally, I would like to thank my family and friends for their support. I want to thank my parents and my brother for encouraging me. Furthermore, I would like to thank Niels Adaloudis for supporting me.

Julia van der Vleuten

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List of Abbreviations

APS	Advanced Planning & Scheduling
ATP	Available to Promise
BOM	Bill of Materials
BSL	Blocked Supply Lines
CAL	Conventional PCBA manufacturing
CLIP	Confirmed Line Item Performance
CPP	Component pre-processing
CR	Clean Room
CHM	Cable Harness Manufacturing
CRP	Capacity Requirements Planning
ERP	Enterprise Resource Planning
HVP	High Volume Production
IM	Injection Molding
IS	Information System
KPI	Key Performance Indicator
MAG	Magnetics
MAP	Material Availability Planning
MCH	Machining
MPS	Master Production Schedule
MRP-I	Material Requirements Planning
MRP-II	Manufacturing Resources Planning
OHS	On-Hand Stock
PT	Prodrive Technologies
RCCP	Rough-Cut Capacity Planning
RCRO	Rounded consistent appropriate share with run-out time leftovers
RLIP	Requested Line Item Performance
SA	System Assembly
SCOP	Supply Chain Operations Planning
SCP	Supply Chain Planning
SMD	SMD PCBA manufacturing
S&OP	Sales & Operations Planning

WIP	Work in Progress
WPE	Work Preparation Engineer
WSH	Workshop

1 Introduction

This master thesis is part of the master's program Operations Management & Logistics at the Eindhoven University of Technology and provides a framework to support the design of supply chain processes with a focus on master planning. Supply Chain Planning (SCP) is defined as the coordination of resources to manage the delivery of products, services and information by balancing supply and demand. SCP has a great influence on supply chains and affects the operational performance of companies that are part of the supply chain (Wiers & de Kok, 2017). SCP can be complex and comes with various challenges. Therefore, it is crucial to manage planning effectively. To support the management of complex planning tasks, Advanced Planning & Scheduling (APS) systems are introduced. An APS system is an interactive tool with a graphical user interface, an engine to recalculate the consequences of planning actions on the plan and a model of the problem that needs to be planned (Wiers & de Kok, 2017). Prodrive Technologies (PT) is one of the companies that uses an APS system to cope with complex planning tasks. The problems at the planning department of PT include an unstable planning, high workload, inefficient planning and an unnecessary high amount of stock. These are typical symptoms related to neglecting material and capacity availability when creating due dates of planned work orders (Wiers & de Kok, 2017). Creating due dates of planned work orders is referred to as master planning. More specifically, master planning generates the due dates of work orders based on the route, capacity, material availability and sales plan (Wiers & de Kok, 2017). The term "planned order" is used to refer to a planned work order as this is in line with the terminology at PT.

In order to implement a master planning logic that takes capacity and material availability into account, PT anticipates the use of an APS system for master planning as the current Enterprise Resource Planning (ERP) system only provides limited support. Wiers and de Kok (2017) confirm this as they state ERP systems often only produce a to-do list that needs to be controlled by a human planner. The new APS system, with master planning that creates a material and capacity feasible plan, should improve the work center output, the make-span of products, the stock level, the Confirmed Line Item Performance (CLIP) and Requested Line Item Performance (RLIP) on production and sales orders and the number of planners needed to make a production plan. In order to successfully implement master planning using APS, the related processes and procedures need to be defined and managed (Rudberg & Cederborg, 2011). PT also indicates that a structured and comprehensive overview of master planning processes is required in order to implement master planning using APS. Therefore, this research aims to solve the master planning problem of PT. In addition, it is intended to provide a contribution to existing scientific knowledge by developing an integrated SCP framework that supports the design of master planning processes by describing the related processes.

The thesis starts with an introduction including background information regarding the company, problem context and research aim. In section 2, the research methodology is discussed. Section 3 includes the design of an integrated SCP framework. This framework is used to design the master planning processes at PT in section 4. Also, an analysis of the planning logic is presented here. In section 5, the integrated SCP framework and proposed master planning processes are evaluated. Section 6 includes the conclusion and discussion.

1.1 Background Prodrive Technologies

PT develops and produces high-tech products, systems and technology-driven solutions. The company was established in 1993 and has reached a turnover of 304 million euros in 2021. They have regional headquarters in Boston (USA) and Suzhou (China) and corporate headquarters in Son (The Netherlands). This master thesis will be conducted in Son at the planning department. The company specializes in designing and manufacturing electronics, software and mechanics. Their innovative approach includes the usage of unique and efficient process techniques and in-house development. PT has six technology programs, namely Embedded Computing Systems, Motion & Mechatronics, Power Conversion, Vision & Sensing, Industrial Automation and Contract Manufacturing Services. These technologies are used in the Semiconductor, Industrial, Infrastructure & Energy, Medical and Mobility Solutions market. They aim to minimize time-to-market, risks and costs. PT identifies eleven product manufacturing processes in their internal supply chain, namely Conventional PCBA manufacturing (CAL), SMD PCBA manufacturing (SMD), System Assembly (SA), Clean Room (CR), Magnetics (MAG), Cable Harness Manufacturing (CHM), Injection Molding (IM), Component pre-processing (CPP), Workshop (WSH), Machining (MCH) and High Volume Production (HVP). Figure 3 shows the supply chain within PT. More specifically, it shows the different product manufacturing processes and how they are related. This provides an overview of the vertically integrated processes and how a replan or reschedule action of orders (e.g. due to material shortages) might trigger many subsequent actions in the downstream departments. It can be seen that, for example, if CHM misses a part, not only does it affect the planning of CHM, but possibly also the planning of MAG, SMD, CAL, SA and/or CR. This project covers the planning related to all departments shown in Figure 3. An explanation for each department is given based on the explanation provided by PT. This information provides context regarding the complexity related to the planning process.

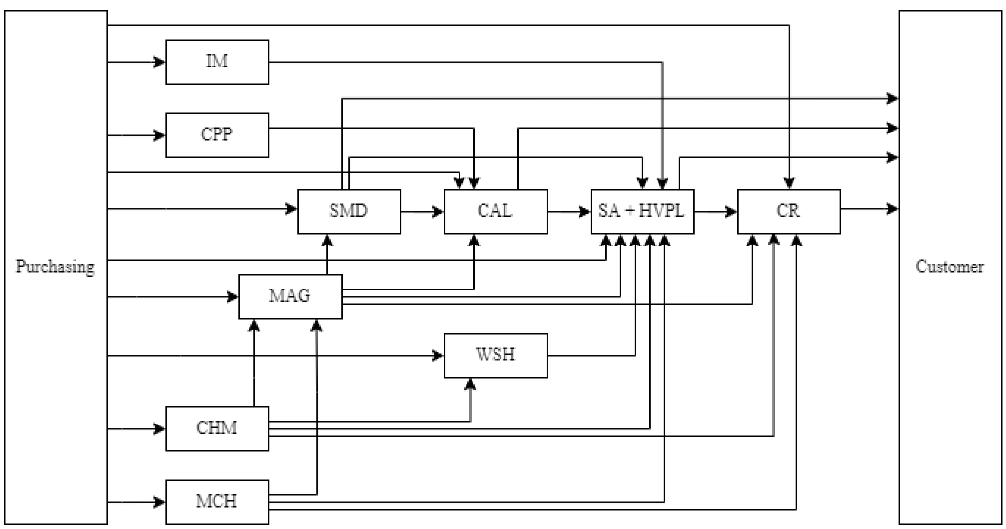


Figure 3: Departments at Prodrive Technologies

- **MCH**: The MCH product manufacturing process starts with the checking of programs, instructions, routers and tooling requirements by the Work Preparation Engineer (WPE). After material and workstation preparation, the workpiece is pressed, milled and turned. Next, the workpiece is Wire Electrical Discharged, deburred and cleaned. Lastly, the workpiece is inspected using measurements, gaging or visual inspection by the inspector. Field returns related to the process, costs of poor quality, CLIP, RLIP and scrap parts per million are each used as Key Performance Indicator (KPI).

- **IM**: The first step in the IM process is the preparation of the order. Here, the Bill of Materials (BOM), order quality and tooling availability is checked by the WPE. Also, additional parts are manufactured using 3D printing. Next, parts are molded, and markings are printed on the product. Lastly, the foam on the product is dispensed and the technician performs a visual inspection. The KPIs involved in IM are field returns related to the process, costs of poor quality, CLIP, RLIP and scrap parts per million.
- **CHM**: CHM starts with a check by the WPE regarding the programs, instructions, routers and tooling requirements. Next, the technician focuses on the cutting, stripping, dismantling, marking and pre-assembly for the operation configuration. Afterwards, the technician is responsible for crimping and soldering as part of the connection step. Subsequently, the technician assembles and performs any related tasks. Next, the product is tested and inspected. The KPIs related to CHM are field returns related to the process, costs of poor quality, CLIP, RLIP and scrap parts per million.
- **MAG**: First, the WPE checks the components, machinery, tooling and production files. Next, the technician is responsible for winding, welding and assembly. Subsequently, potting, impregnation, magnet assembly and testing is performed. Lastly, the order is visually inspected by the inspector. The KPIs that are used for MAG are field returns related to the process, costs of poor quality, CLIP, RLIP and scrap parts per million.
- **SMD**: The SMD product manufacturing process begins with the work preparation performed by the WPE. Here, the WPE checks the machine files, tooling and equipment for the order. Next, all feeders are loaded with tapes by the technician. The technician is also responsible for the marking of the PCB with the serial number barcode. Subsequently, the solder paste is printed on the PCB and if required the paste is jetted on printed circuit board. Furthermore, the paste is automatically inspected. Next, the components are picked and placed on the board after which it is inspected. Also, the components are soldered on the printed circuit board and the component solder joints are inspected. Lastly, passive components are tested. For SMD, the applicable KPIs are number of placed components, cost of poor quality, field returns related to the process, CLIP, RLIP and scrap parts per million.
- **CAL**: CAL starts with the preparation of all machine files, tooling and equipment by the WPE. Next, the components are pre-processed, which is called CPP as shown in Figure 3. If required, the components and conventional components are assembled, automatically and manually placed onto the printed circuit board. Subsequently, selective wave soldering is executed which entails soldering through hole pins. Next, the solder joints of the printed circuit board are inspected. The following step is press fit of components on the printed circuit board after which In Circuit Testing and Automatic Electrical Testing is performed if necessary. Also, underfill material and coating is applied to the printed circuit board if required. This is automatically inspected and if required the products are depanelized. The applicable KPIs for CAL are field returns related to the process, costs of poor quality, CLIP, RLIP and scrap parts per million.
- **SA**: For SA the WPE starts with the preparation of programs, information, instructions, routers and tooling necessities. Next, the technician is responsible for the assembly and other activities such as dispensing, screwing, heat staking, ultrasonic welding and labelling. For SA the monitored KPIs are field returns related to the process, costs of poor quality, CLIP, RLIP and scrap parts per million.

1.2 Problem context

In order to align the production orders with the production capacity of PT, a planning process is followed. This process belongs to Planning, which is part of the Supply Chain Management department. The planning process, as visualized by PT itself, is shown in Figure 4. This process provides a general overview of the current planning process at PT. Below, a description of the planning process is provided.

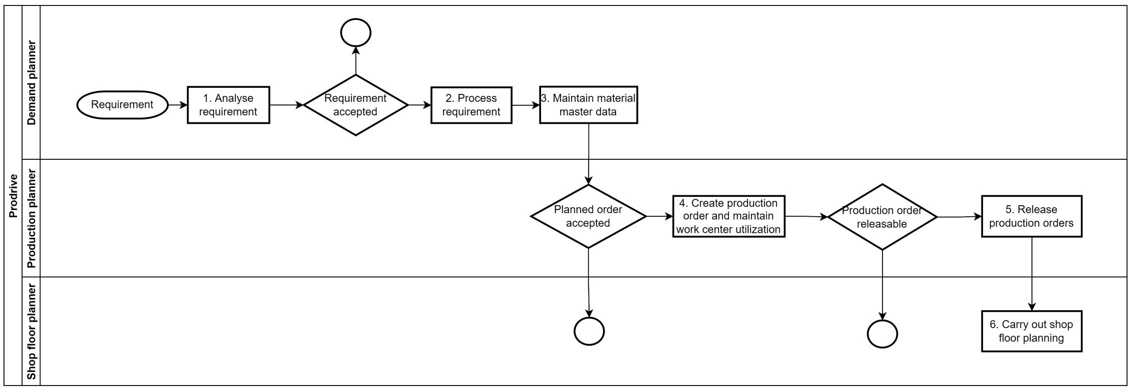


Figure 4: Planning process according to Prodrive Technologies

1. When a requirement arrives, it is analyzed by the demand planner. Here, the forecast, supply risks and material reservations are checked.

2. The requirement is rejected or accepted based on the internal capacity, lead times, safety stock and sales order/forecast. If the requirement is rejected, the customer is informed. If the requirement is accepted, it is processed in the system. The Material Requirements Planning (MRP-I) run is responsible for the creation and updates of planned orders.

3. When production should start within four weeks for an order, the production planner is granted ownership for the order and checks whether the planned order can be converted to a production order. This means that the production planner checks whether all required materials are expected to arrive in time. If the materials are not expected to arrive before the required date, the production planner assesses the expected arrival time and whether it is an internal or external part. The production planner can consider the expected arrival times as pessimistic and convert the planned order nevertheless, yet this imposes a material shortage risk. When it is very unlikely that the materials will be available on the required date, the planned order needs to be moved to a later date. This has to be discussed with the demand planner.

4. When the planned order is converted it becomes a production order. Here, the Blocked Supply Lines (BSL) is used to maintain a feasible planning. The BSL is an excel file in which material unavailability is described. The blocked supply per order and expected supply dates are provided for all blocked supply-demand allocations in the supply chain. This list is used by the purchasing department, production planners and demand planners.

5. Production can be started by releasing the order. In general, order releases can only take place if all required material are available. It is possible to release orders with missing parts as an exception. Yet, this is based on the assessment of the production planner.

6. Logistics starts picking all required materials when the order is released. Furthermore, the

shop floor planner needs to make sure the planning is carried out and informs the production planner when delays occur.

To get a better understanding of planning at PT, an UML class diagram is created (Figure 5). ProductLocation denotes the relation between a product and the location at which the product can be consumed and/or produced. External supply lines and independent demand are examples of external supply and demand, whereas the internal consumption/production is represented by the entire left-hand side of the graph. External supply lines consist of purchase orders and purchase requisitions. Independent demand consists of sales orders, forecast and internal demand. On the top left, it can be seen that a location can have resources and machines. Operations are assigned to resources and machines and have ResourceDuration and MachineDuration associated to the relation. Furthermore, a product has one or more BOMs and one or more routers. A router consists of one or more operation(s).

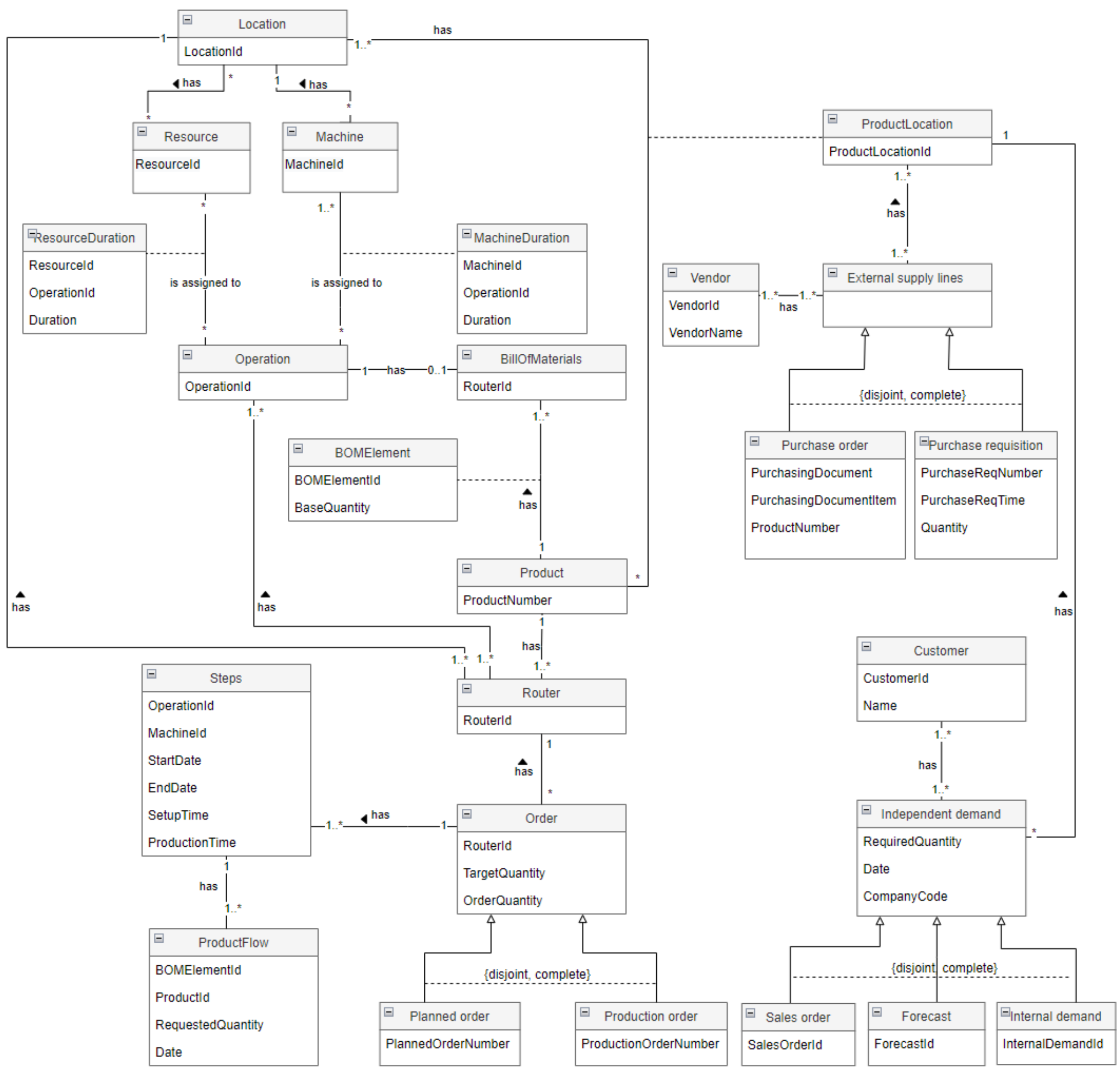


Figure 5: UML class diagram of planning at PT

The bottom left part of the diagram shows the order, steps and ProductFlow objects. An order can be a planned order or production order. A planned order is converted to a production order when it enters a time horizon of four weeks. Planned and production orders are represented by the order 'object', which has a selected router and a step for each operation within this router. These steps include the operation, machine, start date, end date, set-up time and production time. The steps have a ProductFlow which includes the BomElement and requested quantity.

1.3 Management problem statement

The challenges at PT include vertical integration and horizontal integration. Additional planners need to be hired to handle the increasing complexity. At the same time, the marginal output of a new FTE is slowly decreasing, as it also results in additional overhead, interdependencies and lack of overview. Based on data analyses, exploratory interviews and observations, four main master planning problems are identified at PT. These include planning instability (1), an inefficient planning (2), high workload (3) and an unnecessary high amount of stock (4). Firstly, the planning at PT is unstable. For some departments, the production orders are only scheduled one week in advance. In the second week, the orders are not scheduled yet. Given the number of orders and limited capacity, it is not possible to execute all those orders at the same time. Therefore, the planning is not feasible and unstable. Also, a significant part of the orders are blocked for the upcoming 20 weeks. Blocked orders are orders where at least one requirement cannot be consumed from (safety) stock and arrives late. That means that the planning has to change in order to make it feasible. Secondly, it has been observed that individual planners make independent decisions regarding priorities, resulting in misalignment and inefficiencies. Thirdly, there has been a significant increase in the number of planners in the past five years. This increase is relatively large compared to the growth in revenue of PT. The last symptom is related to the unnecessary high amount of stock. When materials are missing in a lower BOM level, all other departments related to the same final product should also delay planned production. However, the other parts in the BOM are still purchased/produced at the initial date, since the orders are not postponed. This means that unnecessary stock is built up. More details regarding the symptoms are provided in Appendix A. The following management problem is identified:

The master planning process at PT is ineffective, causing too much work and too much inventory.

1.4 Problem analysis and diagnosis

This thesis aims to provide a contribution to literature. Therefore, the master planning problems identified at PT are compared to master planning problems described in literature. One of the main master planning problems identified in literature is planning instability. The instability of planned orders is called nervousness (Blackburn, Kropp, & Millen, 1986; Mather, 1975). This problem related to master planning is addressed extensively in literature (Schouten, 2018). Nervousness results in changes in the planning, which causes the need to expedite supply or move the supply date to a later point in time. When the supply date is moved to a later date, it can result in additional stock. In general, these adjustments in planning lead to reduced productivity, increased costs, higher throughput times, additional stock, confusion on the shop floor and loss of confidence regarding planning (Hayes & Clark, 1985; Heisig, 2002; Schouten, 2018). Also, capacity utilization and customer service levels are likely to decrease (Heisig, 2002; Schouten, 2018).

There are multiple causes identified in literature. One of the main causes of planning instability is MRP-I. MRP-I is a logic that creates planned orders. According to Wiers and de Kok (2017)

MRP-I has two key aspects:

- Material explosion: The BOM indicates what and how many materials are needed to create an end item.
- Lead time offsetting: The time that is needed to produce a component is used to determine when the components need to be produced.

The planned orders created by MRP-I tend to be infeasible. The infeasibilities are due to the fact that the MRP-I logic neglects material availability constraints, does not support finite capacity planning and violates the assumption of fixed lead times (Wiers & de Kok, 2017). These infeasibilities are described by Wiers and de Kok (2017) and require a human planner to adjust the planning. A more detailed analysis of MRP-I is provided in section 4.

Besides the planning logic, several process-related causes have been identified at PT. These include material and capacity reservation, the focus of planners and urgency. First of all, it might be known that it is very unlikely that an order can be produced due to limited capacity or materials. Delaying an order cannot always be undone at a later point in time, because initially allocated materials can be reallocated to other orders in the meanwhile. Therefore, some planners avoid moving the order to reserve capacity and materials. However, this results in an unrealistic planning. Second of all, no one oversees the full supply chain. The production planners are responsible for their department, while demand planners are responsible for the order for their customer. Lastly, when a product has several BOM layers and contains one missing part in one of the lower layers, every layer should be delayed. This does not always happen as moving the order to a later date means that the order does not seem urgent, and procurement does not actively try to obtain the missing part.

As described above, several problems related to master planning are described in literature. Some of them are also identified at PT. The problems are compared in this paragraph. First of all, planning instability is the main problem related to MRP-I according to Wiers and de Kok (2017). An unstable planning is also detected at PT. Hayes and Clark (1985) mention that productivity can decrease when dealing with an unstable planning. This productivity can be related to the planning efficiency symptom observed at PT. Also, increased costs are identified as a result of planning instability in literature. The costs also increase at PT when considering the increase in human planners and additional stock. In literature, additional stock is also identified as a problem related to changes related to planned orders (Hayes & Clark, 1985). This indicates that nervousness related to MRP-I likely affects PT too. The higher throughput times, confusion on the shop floor, loss of confidence and capacity utilization are not verified in this project. However, further analysis might indicate that these issues are also present at PT. The symptoms and causes of the master planning problems at PT, which are identified in literature, are shown in the cause and effect diagram in Figure 6.

Based on the analysis above, it can be concluded that one of the main causes of problems related to master planning is the MRP-I logic, which does not take material and capacity availability into account (Wiers & de Kok, 2017). Thus, when implementing master planning it is crucial to use a logic that creates a material and capacity feasible planning to solve the problems identified at PT and in literature. This logic should be linked to effective master planning processes. As there is no comprehensive and structured overview of master planning processes in literature, it is necessary to develop a framework that provides an overview of SCP and supports the design master planning processes.

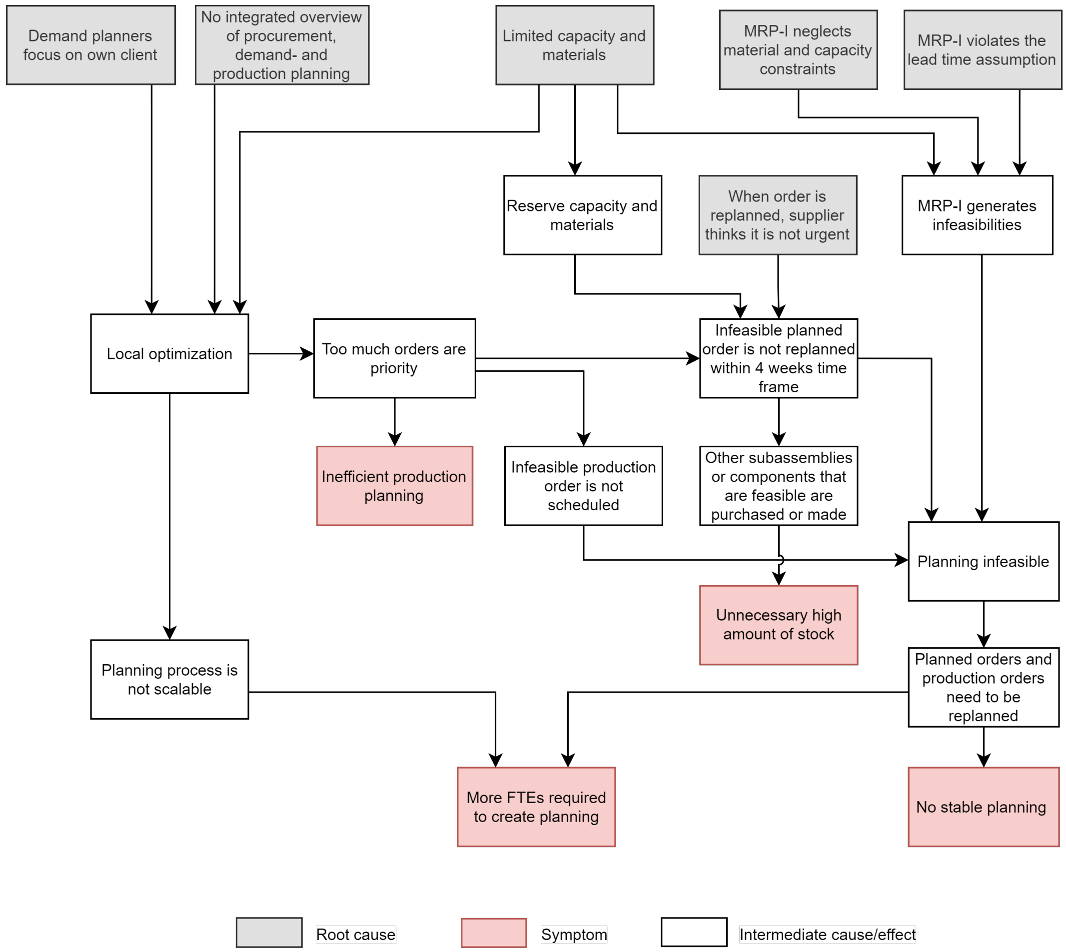


Figure 6: Cause and effect diagram

1.5 Objective

This research aims to create a framework that supports the design of master planning at PT by describing the related processes. The following two elements are identified that remain unaddressed until now:

- A general theoretical framework that supports the design and implementation of master planning.
- The application and evaluation of a SCP framework at Prodrive Technologies to support the design and implementation of master planning.

The planning challenges identified at PT are known in literature. This research proposes the development of a framework within manufacturing operations management with a focus on SCP. This means that a new solution is developed for known problems. When relating this to the framework of (Gregor & Hevner, 2013) (Figure 7), such research is referred to as "Improvement". Here, a research opportunity and knowledge contribution are elements of this research.

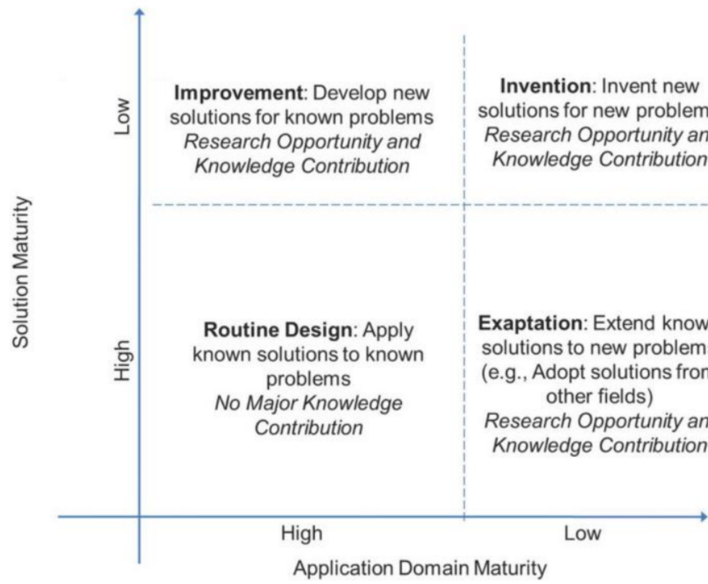


Figure 7: Knowledge contribution framework of design science research (Gregor & Hevner, 2013)

This results in the following objective of this thesis:

To develop a supply chain planning framework that supports the design of master planning processes using APS with the aim to improve the planning processes at PT.

1.6 Scope

Table 2 provides an overview of the parts that are in and out of scope for this research project.

In scope	Out of scope
Design of a general framework that describes the detailed processes and procedures related to master planning and how these relate to SCP.	Implementation of the master planning processes at PT.
An overview of how a material planning logic can improve the planning process and how this can be supported by master planning.	Detailed processes and procedures of other tasks that are unrelated to master planning.
Evaluation of the general framework at PT.	

Table 2: Scope

1.7 Research questions

As described before, master planning which takes material and capacity availability into account can improve planning. It should help companies with a complex planning context such as PT deal with the current challenges in the planning department. Therefore, there exists a practical incentive to develop a framework that will guide the company to successfully design master planning processes. Therefore, the following research question is defined:

How can the design of master planning processes using APS at PT be supported by a supply chain planning framework?

1. *Which concepts are part of master planning and how are these related to supply chain planning?*
2. *Which aspects should be part of an effective master planning process based on a supply chain planning framework?*
3. *How can a material planning logic improve the planning process and how can the master planning process support this logic?*
4. *How can a supply chain planning framework help a company to design master planning using APS?*

1.8 Research gap

A successful implementation of master planning using APS is reliant on well-defined and managed processes and procedures (Rudberg & Cederborg, 2011). This is also established by PT as they require detailed and elaborate process descriptions to change the current way of planning. In literature, much research focuses on the master planning module of an APS system and the creation of a logic to create planned orders (de Kok et al., 2005; Steinrücke & Jahr, 2012). Also, some general frameworks and information is provided in literature regarding master planning processes (Fleischmann & Meyr, 2003; Stadtler, Kilger, & Meyr, 2015). However, it is not specified how master planning should be linked to other parts of SCP. This is required to obtain an overview of the supply chain planning processes (1), structure the planning process including the dependencies and flows between different parts of planning (2) and have detailed input to design the new master planning processes (3). Also, the organizational processes and procedures that are part of master planning are not addressed in detail. Given the importance of describing the master planning processes (Rudberg & Cederborg, 2011), an overview of the processes and procedures related to master planning would be a valuable addition to literature. According to PT, this would be useful in practice as an elaborate framework would support the design and implementation of master planning (Rudberg & Cederborg, 2011). PT can be classified, using the V-A-T classification described by Umble (1992), as an A-plant. That means that the product flows are characterized by convergent assembly points throughout the production process (Umble, 1992). Therefore, PT is a representative of assembly companies that are classified as an A-plant. This indicates that the design of a SCP framework becomes scientifically relevant as the problem is generic for A-plant production environments. This result in the following research gap that will be addressed by designing a SCP framework that supports the design of master planning processes:

A comprehensive and structured overview of the master planning processes remains to a large extent unaddressed in literature, even though this is crucial for the successful implementation of the master planning APS module.

2 Research Methodology

This section describes the methodology of this research. The information systems research framework of Hevner et al. (2004) is used to structure the project. The framework is shown in Figure 8 and consists of the environment, knowledge base and Information System (IS) research lane. The environment lane shows the input from PT and output from the IS research lane that can be used by PT. The knowledge base lane shows the applicable knowledge and additions to the knowledge base which are generated in the IS research lane. The IS research lane describes the elements which are part of this project. To structure these elements, the regulative cycle of van Strien (1986) described by Van Aken and Berends (2018) is used.

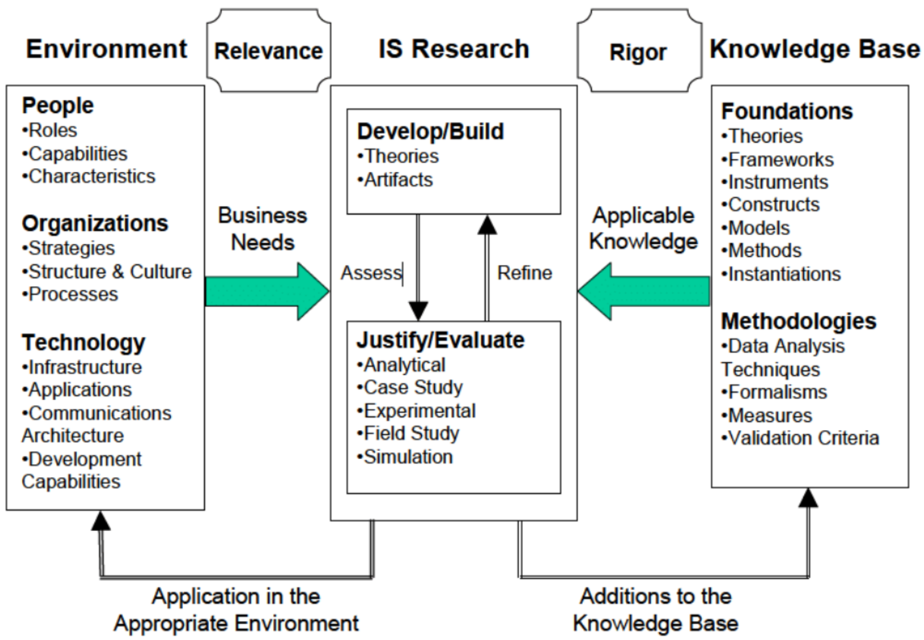


Figure 8: Information systems research framework by Hevner et al. (2004)

The regulative cycle by van Strien (1986) is shown in Figure 9. The regulative cycle describes five steps, namely problem identification, analysis & diagnosis, design, application and evaluation. The regulative cycle is suitable for this research as it aims to develop solutions to field problems. As this research aims to contribute to literature by creating a general SCP framework to support the design of master planning, the regulative cycle is combined with the design science research methodology by Peffers, Tuunanen, Rothenberger, and Chatterjee (2007). It is suitable for this research as the problem is further analyzed and solved using literature. Figure 9 shows the regulative cycle integrated with the design science methodology and covers the methodology of this thesis.

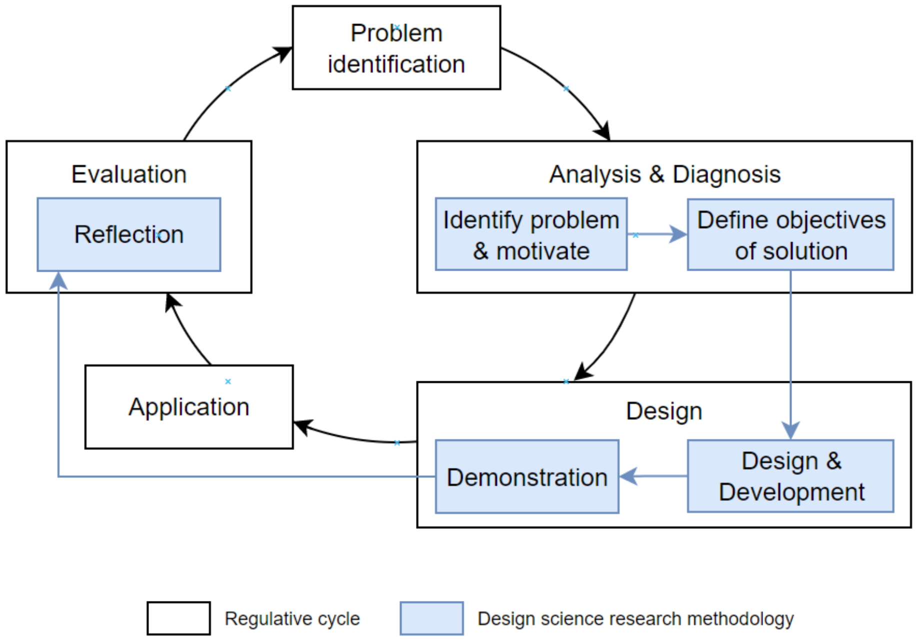


Figure 9: Regulative cycle by Van Aken (1986) including Design science research methodology by Peffers (2008)

Problem identification: In the first step of the regulative cycle, the problem at PT is defined using exploratory interviews and observations. This step answers a part of sub-question 1 by providing more insight into master planning and the problem context. The results of the problem identification phase can be found in section 1. *Outcome: Problems related to master planning identified at PT.*

Analysis & Diagnosis: The analysis step includes an analysis of the current planning process at PT. A cause and effect diagram is developed based on unstructured interviews conducted at PT, observations, a data analysis and a literature review. The problem is identified and it is described how this thesis intends to solve it. As this research aims to provide a contribution to literature, the design science research methodology is initiated. The "identify problem & motivate" and "define objectives of solution" steps are part of the analysis & diagnosis step of the regulative cycle (shown in Figure 9.

- Identify problem & motivate: Here, it is identified that the design science research methodology is needed to create a SCP framework based on literature in order to design the master planning processes.
- Define objectives of solution: In this step, the aim of the design science research methodology sub-process is defined. This includes an analysis of what is required from the SCP framework based on literature in order to support the design of master planning processes.

The results of the analysis step can be found in section 1. The result of this analysis contributes to answering the first research question. This analysis also serves as input for the second research question as it reveals the problems that need to be solved by an effective master planning process. *Outcome: Overview of problems and processes related to master planning at PT. Also, master planning problems in literature are described. Furthermore, the problem context, problem statement,* *objective and scope are determined.*

Design master planning processes: In the design step, the master planning processes are defined. In order to create these processes, it is necessary to have an overview of SCP. Therefore, it is needed to execute the "design & development" step of the design science research framework and create a general SCP framework that supports the design of master planning. This framework is used to show which aspects of SCP are missing in the SCP process at PT. Material coordination is described in further detail since a material feasible planning is a crucial aspect of an effective master planning process. This includes a comparison between MRP-I and a planning logic that takes material availability into account. This provides an answer to the second sub-question as it shows which aspects should be part of an effective master planning process.

- Design & development SCP framework: This step includes the comparison of SCP frameworks retrieved from literature using a systematic literature review. Based on existing frameworks an integrated SCP framework is designed. This framework provides an overview of SCP with a focus on master planning. Therefore, the framework reveals how master planning is related to SCP and which processes are important to consider when designing master planning processes.
- Demonstration SCP framework: In this step, the SCP framework is used to design the master planning processes at PT.

In the design step of the regulative cycle, the master planning aspect of the framework is described in further detail based on the needs and constraints defined by PT. The master planning processes are visualized using "ArchiMate (Version 4.10.0)" (2022). ArchiMate is a technique to model processes using different views. ArchiMate is suitable for this project as it visualizes complex processes and can be used to assess the impact of design choices. For specific processes defined in ArchiMate, the IDEF method is used to model input, output, resources and constraints. A more detailed description of the techniques is provided in section 5. This step answers the third sub-question as the section shows how a material planning logic can improve the planning process and how master planning processes support the logic. This step contributes to answering the third research question. This can be seen in sections 3 and 4. *Outcome: An overview of SCP frameworks in literature and an integrated SCP framework to support the design of master planning processes is provided. Also, the result of using a material feasible planning logic has been analyzed with a case study at PT and master planning processes are designed that support such a logic.*

Application & Evaluation: In this step, it is described how PT uses the SCP framework and master planning processes. The face validity will be indicated by stakeholders including the problem owner at PT since it is not within the scope of this project to implement the master planning processes. Unstructured interviews are used to check the validity. Furthermore, the master planning processes created in the design step of the regulative cycle are based on the needs and constraints defined by PT. This is evaluated in this step as these needs and constraints might not result in the best master planning process. At the same time, parts of the designed process might generate new insights. Therefore, this evaluation leads to adjustments of the processes and framework. It may also lead to a restart of the regulative cycle or design science research methodology; however, the restart is out of the scope of this project. The result of this step can be seen in section 5. Moreover, the evaluation step answers the fourth research question as it reveals how a SCP framework can help a company to design master planning. *Outcome: Master planning processes and SCP framework evaluated at PT.*

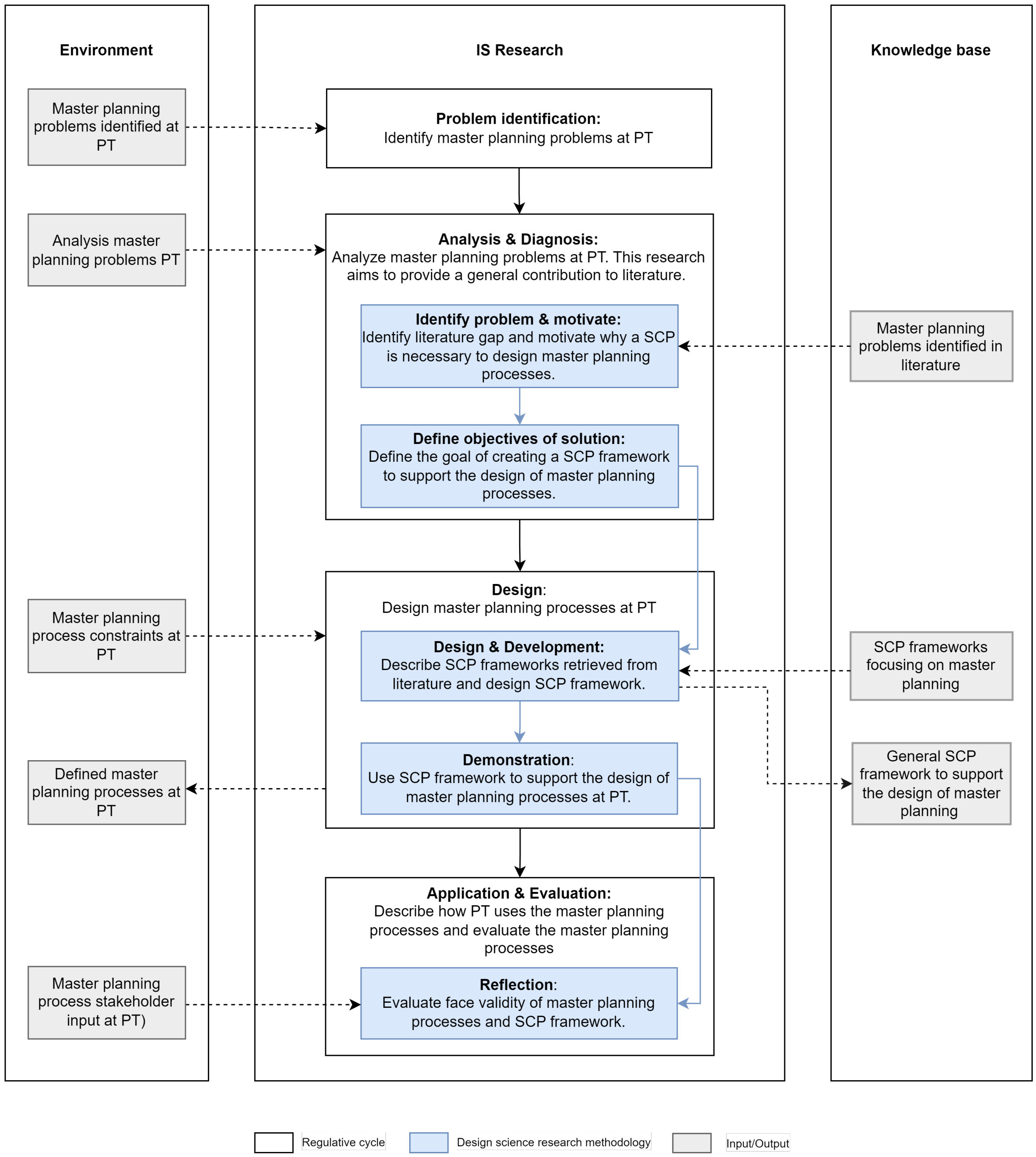


Figure 10: Information systems research framework based on Hevner et al. (2004), Van Aken et al. (2018) and Peffers (2008)

3 Design SCP Framework

3.1 Analysis SCP frameworks

In this section, existing SCP frameworks are analyzed and compared using the systematic literature review that is part of this graduation project. The most relevant frameworks are described below. This analysis provides an overview of the SCP processes related to master planning and is part of the design SCP framework step of the Design Science Research Methodology.

3.1.1 SCP Matrix and APS modules

The first framework is the SCP matrix. The SCP is described by most retrieved papers in the systematic literature review (Fleischmann & Meyr, 2003; Stadtler et al., 2015; Raubenheimer & Stammen-Hegener, 2013; Stadtler, Fleischmann, Grunow, Meyr, & Sürie, 2011). The SCP matrix is shown in Figure 11. According to Fleischmann and Meyr (2003), the SCP matrix can be tailored to the type of supply chain. The SCP matrix is structured based on two dimensions, namely planning horizon and supply chain process. For the planning horizon, three managerial decision-making levels are defined based on time. The differences between the vertical planning levels are characterized by six aspects (Stadtler et al., 2011). These include hierarchy, planning interval, type of decisions, impact, level of detail and responsibility.

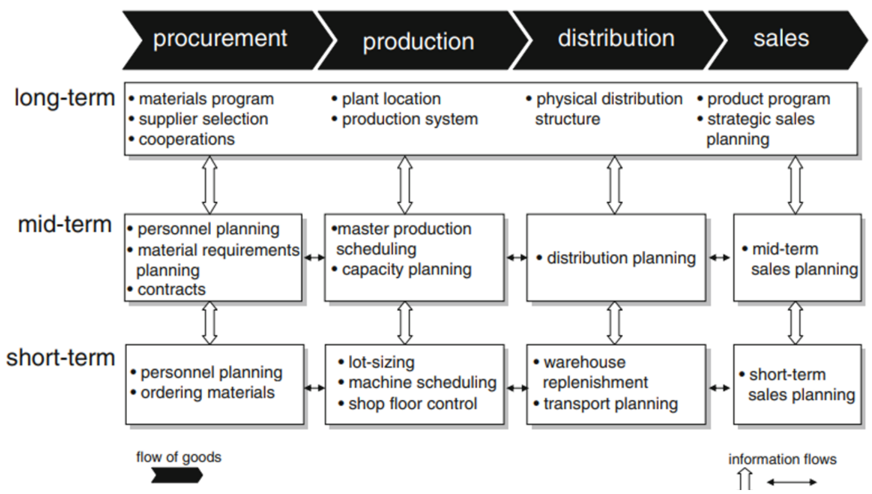


Figure 11: SCP matrix by Stadtler et al. (2015)

The levels are described by Fleischmann and Meyr (2003) and Stadtler et al. (2015) as:

- Long-term: These strategic decisions affect the company for several years. It should reflect the business strategy and physical structure of the supply chain and/or enterprise.
- Mid-term: These decisions are framed by the decisions made by the long-term planning. These decisions usually cover a range from half a year to two years. The decisions aim to provide an outline for the regular operations.
- Short-term: These decisions cover the first few weeks or months. It uses the guidelines from the upper levels to prepare detailed instructions for immediate execution and control.

The basic processes of supply chain management define the second dimension of the SCP matrix.

These include procurement, production, distribution and sales. The planning tasks in different levels and supply chain processes are connected using vertical and horizontal information flows (Stadtler et al., 2011, 2015). The SCP matrix is also used to structure APS systems. As described in section 1, APS systems are a decision support system that can be used when planning problems require more support due to the complexity and size of the problem (Wiers & de Kok, 2017). APS systems are structured using modules, which are based on the SCP matrix and are described by multiple papers. The APS modules as described by Wiers and de Kok (2017) are shown in Figure 12. Figure 13 shows the APS modules as described by Fleischmann and Meyr (2003). For each module, a description is provided below.

- **Strategic Network Design**: This module focuses on long-term strategic decisions that cover multiple planning tasks. These decisions focus on supply chain configuration, which includes the type of products to produce, the markets to be served and the (sizes of) locations to be used for production.
- **Sales & Operations Planning (S&OP)**: S&OP translates the forecast to a plan based on a financial and capacity model. The objective is to establish what the company wants to sell and make, based on customer demand, product added value, and capabilities (Wiers & de Kok, 2017).
- **Master Planning**: Wiers and de Kok (2017) describe master planning as determining the due dates of planned work orders based on the route, capacity, material availability and sales plan.
- **Demand Planning**: The generation of forecasts and taking exceptional influences into account when creating a planning. This also includes safety stocks and what-if analyses according to Fleischmann and Meyr (2003). The plan serves as input for the S&OP and master planning modules.
- **Demand Fulfillment & Available to Promise (ATP)**: Demand fulfillment and ATP is the tracking of customer orders from order entry to delivery. Order promising, due date setting and shortage planning are included. Order promising can use ATP (Fleischmann & Meyr, 2003)
- **Purchasing and Material Requirements Planning**: This module includes the order generation of procured materials, which uses the BOM. This is often outsourced to the ERP system (Stadtler et al., 2015; Fleischmann & Meyr, 2003). According to Stadtler et al. (2015) the APS module includes purchasing planning for materials and components with a focus on alternative suppliers, quantity discounts, lower (contracts) and upper (material constraints) bounds of quantities.
- **Production Planning and scheduling**: The objective of production planning and scheduling is to establish a detailed schedule for each resource of a plant (Fleischmann & Meyr, 2003).

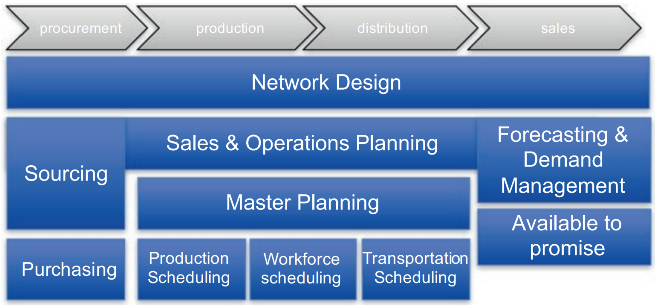


Figure 12: APS modules retrieved from Wiers & de Kok (2018) and based on Stadtler & Kilger (2015)

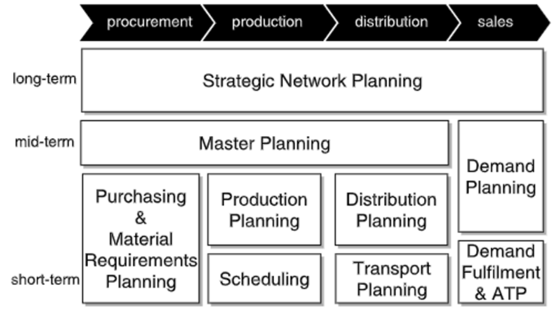


Figure 13: APS modules retrieved from Fleischmann & Meyr (2003)

3.1.2 Production Control Model

The next framework retrieved using the systematic literature study is the Production Control Model by Bertrand, Wortmann, and Wijngaard (1990). The Production Control Model retrieved from Bertrand et al. (1990) is shown in Figure 14. The framework is hierarchical and designed to include decision functions that can be linked to organizational positions. Production control is decomposed of the production control within a production unit and production control at the goodsflow control level. Bertrand et al. (1990) use the term production unit to describe an organized set of resources that take care of a certain phase of production. The goodsflow control level relates to the coordination of the production units and the timing of production and sales. Goodflow control can be divided into coordination and tuning at the aggregate level and at the detailed level.

The aggregate control uses sales and production information and includes settings of production control parameters. These settings of production control parameters include required service levels, lead times, capacity utilizations and stock levels. The input from the sales side is information regarding market potential, accepted orders and quotations. From the production side, information regarding the availability of critical resources, production progress, stock position and restrictions on critical material availability is input. The output of the aggregate control level is the sales plan, (aggregate) purchase and production plan, planned inventory changes, planned availability of resources and a capacity-use plan. This is shown at the top of Figure 14.

Based on the aggregate decisions, the detailed plans per product are created. Load planning and material coordination are considered as separate processes in the detailed control. Material coordination includes the delivery agreements with sales or customers and a plan related to the production volume per production unit. This results in agreements with customers, purchase orders and prioritized work orders to be released to the production units. The dashed arrow indicates the possibility of negotiations between material coordination and production units regarding revisions of released work orders. This should not occur frequently as Bertrand et al. (1990) consider the outputs to be stable. For work order release, the availability of capacity needs to be checked. This is called workload acceptance. Besides the capacity planning and load planning, the production progress per production unit is considered. This decision is used to check whether enough capacity is available to release the work orders, given the due dates (Bertrand et al., 1990). An overview of the definitions from Bertrand et al. (1990) is provided below.

- **Aggregate planning**: The aggregate control results in a number of interrelated plans. On the sales side the aggregate control results in a sales plan on an aggregate level. On the purchasing side the aggregate control results in a purchase plan for critical materials, and in an indication of what to purchase for non-critical materials. On the production side, the aggregate control results in a production plan, planned inventory changes, planned availability of resources (capacity plan) and a capacity-use plan. These must be consistent.

- **Capacity plan**: This plan indicates for each critical resource the capacity that will be available in future periods.
- **Load planning**: The future stream of work orders for the production unit is checked with the available capacity (vice versa).
- **Material coordination**: Material coordination is authorized to make delivery agreements with customers or to make agreements with sales about rules to be used for customer order acceptance.
- **Workload acceptance**: Before work release, the availability of capacity needs to be checked by a decision function called workload acceptance. It takes the already mentioned capacity planning and capacity load planning into account, but also production progress (already accepted orders) per production unit. The aim is to establish whether enough capacity is available to release the work orders, given the work order due dates.
- **Work release**: Work order release combines the capacity and materials point-of-view. Here, a decision is made regarding the amount of work in progress in relation to the available capacity to control the throughput time of released orders.
- **Detailed planning**: Detailed work order planning serves as a base for internal coordination of the department and focuses on a timely realization of the accepted work orders with maximum efficiency given the constraints. Special constraints or requirements can be taken into account.
- **Capacity allocation/Routing**: Allocation of multi-purpose capacity resources to certain parts of the work-in-process. Given that a production unit can increase/decrease capacity on the short term, the capacity allocation allows a production unit to deal with a flexible volume and flexible composition.
- **Work order release**: Selection of the next order or job from the queue of work, and making available materials, tools, documentation, etc. Given the progress of orders in the production unit, and the available flexible capacity, the sequence of orders should be decided.

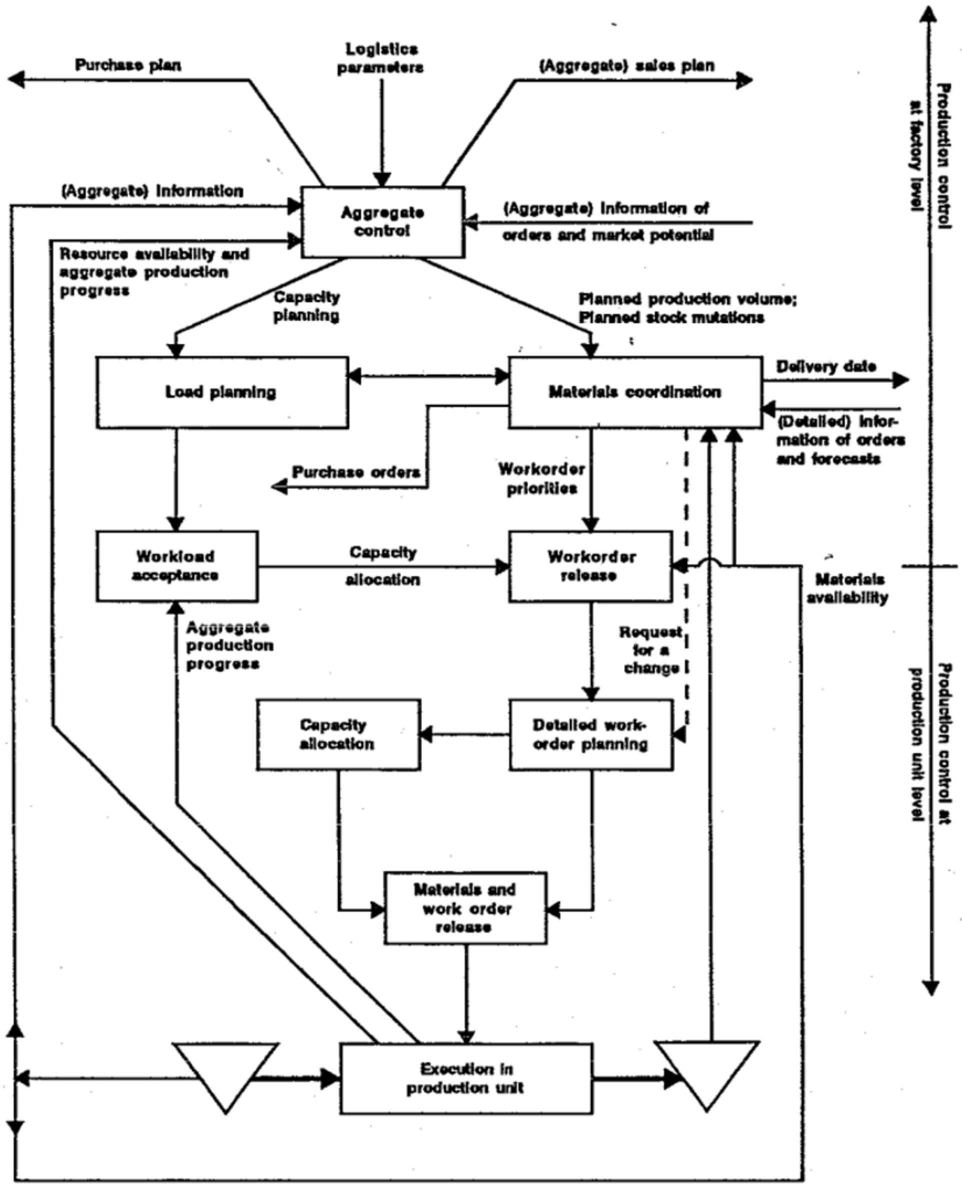


Figure 14: Production Control Model (Bertrand et al., 2004)

3.1.3 MRP-II framework

The last relevant framework retrieved from the systematic literature review is the Manufacturing Resources Planning (MRP-II) framework based on Vollman et al. (1988) and described by Bertrand et al. (1990) and Wiers and de Kok (2017). The framework is shown in Figure 15 and is retrieved from de Kok and Wiers (2016). MRP-II elaborates upon the MRP-I logic. Rough-Cut Capacity Planning (RCCP), Aggregate Planning and Resource planning are used to create a realistic Master Production Schedule (MPS). The RCCP is a technique to validate the MPS in terms of capacity. Furthermore, the MPS should fit into an aggregate planning. In aggregate planning, capacities and critical materials are determined for the long-term. After MRP-I, Capacity Requirements Planning (CRP) validates the output of MRP-I and manual adjustments can be made as a firm-planned order. This indicates that MRP-I cannot change this order. It should be noted that CRP and RCCP are not formally related (Bertrand et al., 1990; Wiers & de Kok, 2017). An overview of the definitions based on Bertrand et al. (1990) is provided below.

- **Resource planning**: Resource planning determines the required long-term capacity on an aggregate level.
- **Aggregate planning**: Aggregate planning needs to make sure MPS fits into this planning. Furthermore, capacities and critical materials are captured for the long term.
- **RCCP**: The aim of RCCP is to create a realistic MPS in terms of the critical capacity constraints. The orders at the MPS level are roughly checked and adjusted (if necessary) based on critical capacity load.
- **Master production scheduling**: Master production scheduling defines what needs to be produced when at the MPS level.
- **MRP-I**: MRP-I is used to calculate order quantities for all items based on the MPS.
- **Order release**: The order is released to production.

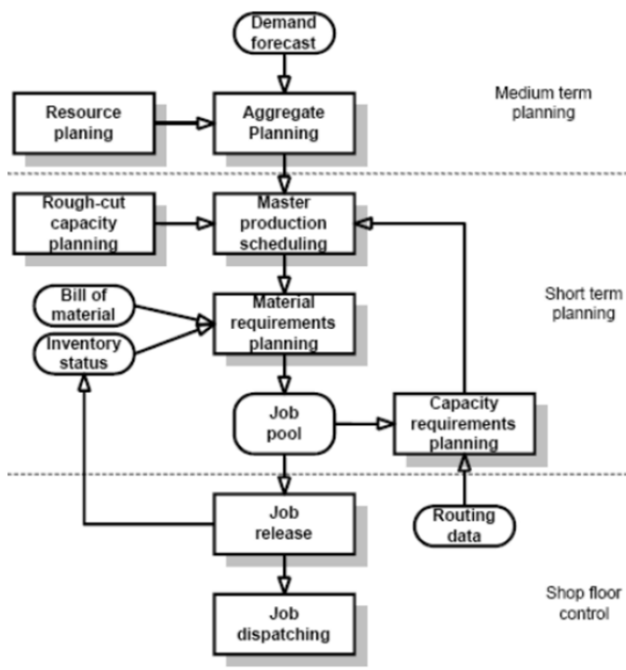


Figure 15: MRP-II framework (de Kok & Wiers, 2016)

In conclusion, this section provides an overview of existing SCP frameworks. In order to understand how these frameworks relate to each other and which function should be part of SCP, the frameworks are compared and integrated. Using a combined framework, an overview of SCP is created. Furthermore, the framework shows how master planning is related to SCP.

3.2 Design of SCP framework

This section presents an integrated SCP framework with an overview of the processes and procedures related to master planning. This SCP framework is part of the "Design SCP framework" step of the Design Science Research methodology.

Literature proposes different ways to structure SCP. The SCP matrix is often used to structure SCP processes (Fleischmann & Meyr, 2003; Stadtler et al., 2011, 2015). The SCP matrix structures the planning tasks using time horizon and planning processes. These horizons are used in the integrated framework. Next, the APS modules described by Wiers and de Kok (2017), Stadtler et al. (2015) and Fleischmann and Meyr (2003) are included in the framework. This is shown in red in Appendix C. The APS modules cover the whole supply chain planning scope with the four business processes shown at the top of Figure 16. The production control model focuses on the production business process and provides more details for the design of master planning processes than the APS modules. To show how both frameworks relate to each other they are combined in one figure. Appendix D shows the production control model in green in the integrated framework. Besides the APS modules based on the SCP matrix and the production control model, the MRP-II framework is retrieved from literature. The MRP-II framework also focuses on the production business process. Appendix E shows the MRP-II framework in orange. Lastly, the scope of Supply Chain Operations Planning (SCOP) is shown in Appendix F. SCOP covers master planning and S&OP. SCOP decides on the release of production orders to all production units within the supply chain (Wiers & de Kok, 2017). SCOP is based on the framework of Production and Inventory Control by Bertrand et al. (1990). However, material coordination and resource planning are integrated in the SCOP function. That means that all orders released are material and resource feasible. This results in the following constraints:

1. The production unit guarantees (close to) 100% due date reliability.
2. Resource availability is taken into account by the SCOP function by formulating it as a constraint.
3. Material availability is taken into account by the SCOP function by formulating it as a constraint (Wiers & de Kok, 2017).

The most common SCOP function is MRP-I. However, MRP-I does not satisfy assumptions 2 and 3 and therefore assumption 1 (Wiers & de Kok, 2017), which results in infeasible plans. Therefore, constrained-based planning has to be included in the planning logic to create a feasible plan.

The framework that integrates the production control framework (Bertrand et al., 1990), the APS modules (Stadtler et al., 2015; Wiers & de Kok, 2017) and the MRP-II framework (Vollmann, Berry, & Whybark, 1988) is shown in Figure 16. This integrated framework shows how different supply chain planning frameworks are structured with a focus on production. When a production control model item can be compared to an item from the MRP-II framework, they are grouped using the white box with a dotted line. Furthermore, the scope of SCOP is shown in relation to the APS modules, MRP-II and the Production Control model. Also, information flows are displayed in the integrated framework using arrows. These information flows indicate how the production control model and the MRP-II framework are connected to the APS modules. Furthermore, the arrows indicate the flow of information in the frameworks. When creating such an integrated framework, certain choices need to be made regarding the position of tasks and modules. The next section elaborates upon these decisions and discusses the integrated framework in detail.

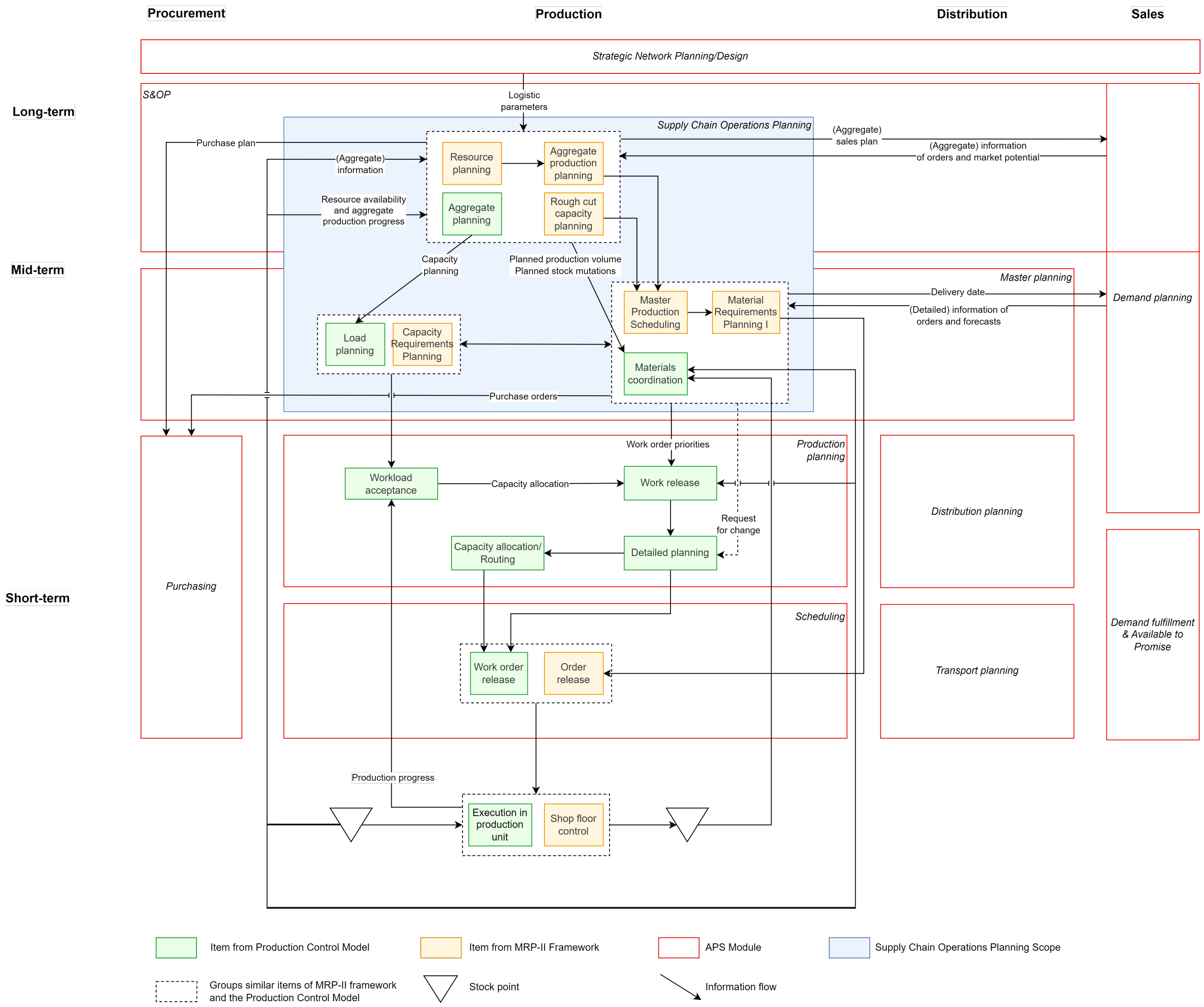


Figure 16: Supply chain planning framework based on literature

Strategic network planning/design focuses on long-term decisions covering procurement, production, distribution and sales. The decisions focus on supply chain configuration, which includes the type of products, markets to be served and the (sizes of) locations to be used for production. The logistic parameters are the output of strategic network planning and are used as input for aggregate planning (production control model) and resource planning, aggregate production planning and RCCP (MRP-II framework).

The aggregate planning from the production control model and the resource planning, aggregate production planning and rough cut capacity planning from the MRP-II framework are similar according to Bertrand et al. (1990). These tasks should ensure that the plan is in line with the long-term sales plan and at the same time respects the purchase plan for critical materials. A significant difference between the production control model and MRP-II framework regarding aggregate planning is that planned stock mutations are only considered at MPS level in the MRP-II framework. The input for aggregate planning (production control model) and resource planning, aggregate production planning and rough cut capacity planning (MRP-II) is (aggregate) information of orders and market potential. This information is provided by the demand planning module.

Furthermore, (aggregate) information, resource availability and aggregate production progress are taken into account (Bertrand et al., 1990). According to Bertrand et al. (1990) output of the tasks is the purchase plan (for critical materials), (aggregate) sales plan, capacity planning, planned production volume and planned stock mutations. The purchase plan is input for the purchasing module and the sales plan is input for the demand planning module. Capacity planning is used by load planning, and planned production volume and planned stock mutations are used by the material coordination process of the production control model. The RCCP and aggregate production planning are used for master production scheduling.

The master planning module includes detailed coordination of material and capacity. The material aspect relates to materials coordination from the production control model and the MPS and MRP-I from the MRP-II framework. The master production scheduling and MRP-I process can be compared to the material coordination of the production control model (Bertrand et al., 1990). Both processes create purchase orders and delivery dates as output. The purchase orders are input for the purchasing module and the delivery dates are used by demand planning. The capacity aspects of the master planning module relate to load planning from the production control model and to capacity requirements planning from the MRP-II framework. CRP can be used for the load planning process, however, that means that CRP is not related to RCCP (Bertrand et al., 1990). In this framework, CRP and load planning are grouped given their similar objective. In MRP-II, the output of CRP can be used by planners to make manual adjustments by creating firmed planned orders, which means these orders can't be adjusted by MRP-I. Furthermore, the output of load planning is used as input by workload acceptance. This is a decision function in the production control model that checks the output of load planning with the existing capacity availability (Bertrand et al., 1990).

In the production control model, the work release combines the material and capacity aspects of master planning. A decision is made regarding the amount of work in progress in relation to the available capacity, to control the throughput time of released orders. All other processes in the framework use the output of work release. The production control model includes detailed planning and capacity allocation. Detailed work order planning focuses on the realization of the accepted work orders with maximum efficiency given the constraints. Special requirements can be taken into account. The material coordination sometimes needs to check with detailed planning whether it is possible to change released work. This is indicated with the dashed arrow. It should be noted that Bertrand et al. (1990) consider this check as an exception. This is different from MRP-II. Capacity allocation is the allocation of capacity resources. Given that a production unit can increase or decrease capacity in the short term, capacity allocation allows a production unit to deal with a flexible volume and flexible composition (Bertrand et al., 1990). Finally, work order release is the selection of the next order or job from the queue of work. Given the progress of orders in the production unit, and the available flexible capacity, the sequence of orders should be decided (Bertrand et al., 1990).

In conclusion, a new SCP framework is designed from the integrated SCP framework based on literature (Figure 17). The new framework shows all functions that should be part of SCP based on the systematic literature review. Therefore, this provides an answer to the research question: "Which concepts are part of master planning, and how are these related to supply chain planning?". This also shows that the MRP-II framework misses some critical functions related to master planning as both load planning and material coordination are not included in MRP-II. More information regarding the shortcomings of MRP-II is provided in the next section. It should also be noted that the Production Control Model includes the relevant functions; however, much manual work is presumed.

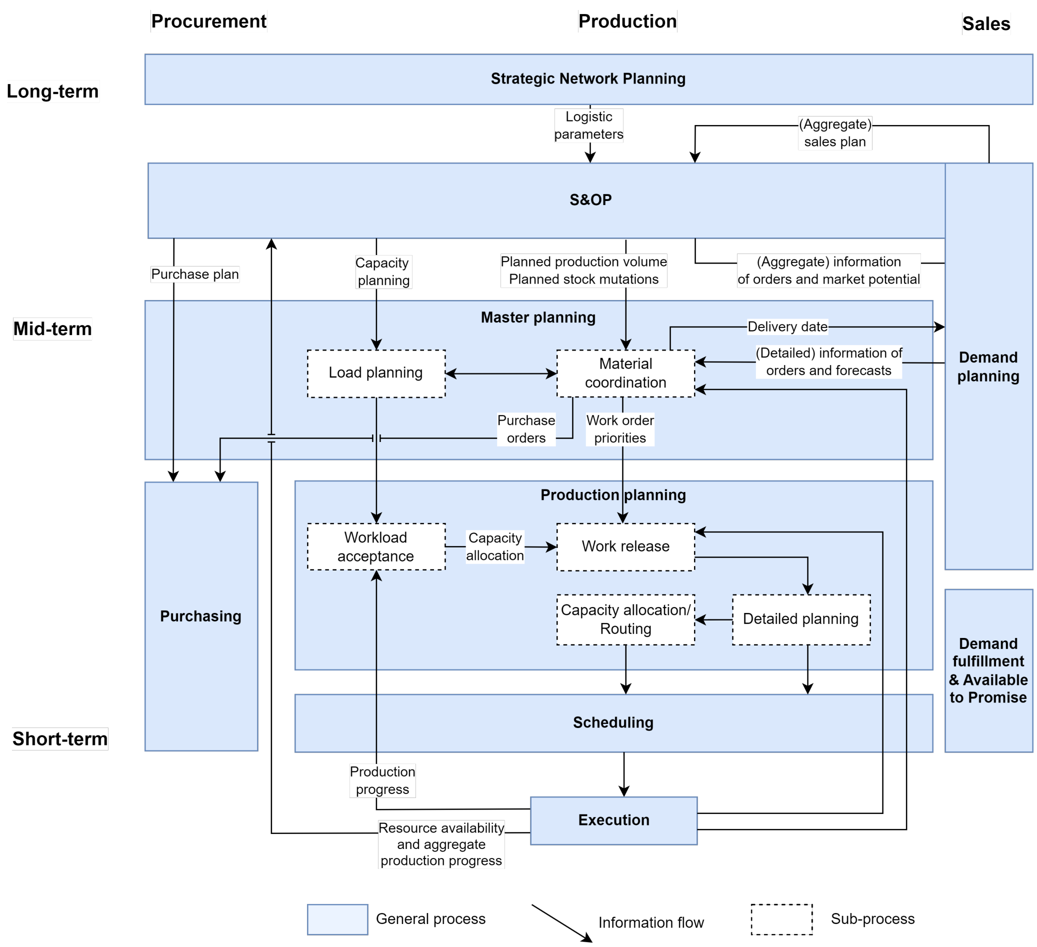


Figure 17: New supply chain planning framework based on literature

4 Design Master Planning Processes

This section shows how a material planning logic can improve the planning process and how master planning processes support the logic. First, the integrated framework is applied to PT. Next, the master planning processes are designed based on the SCP framework. This includes a visualization of the proposed processes. This is part of the ”Design master planning processes” step of the regulative cycle. Furthermore, a logic that accounts for material availability is discussed.

4.1 SCP framework applied to PT

In Figure 18, the framework obtained in the design phase, is applied to the current situation at PT. The grey parts are not part of SCP at PT. Many functions that are part of SCP do not exist at PT. For some parts of SCP, this is due to the type of company and products. For example, distribution planning and transport planning do not need APS support. However, material coordination and load planning are relevant for PT, given the complex BOM structures of many products and limited capacity and material availability. These functions are currently not executed at PT, which indicates that master planning is currently insufficient for PT, especially when neglecting material and capacity availability. This relates back to the main cause of the master planning problems at PT and shows that the MRP-II framework misses crucial functions related to master planning. To get a better understanding of material coordination, the MRP-I logic is compared to a material feasible logic below.

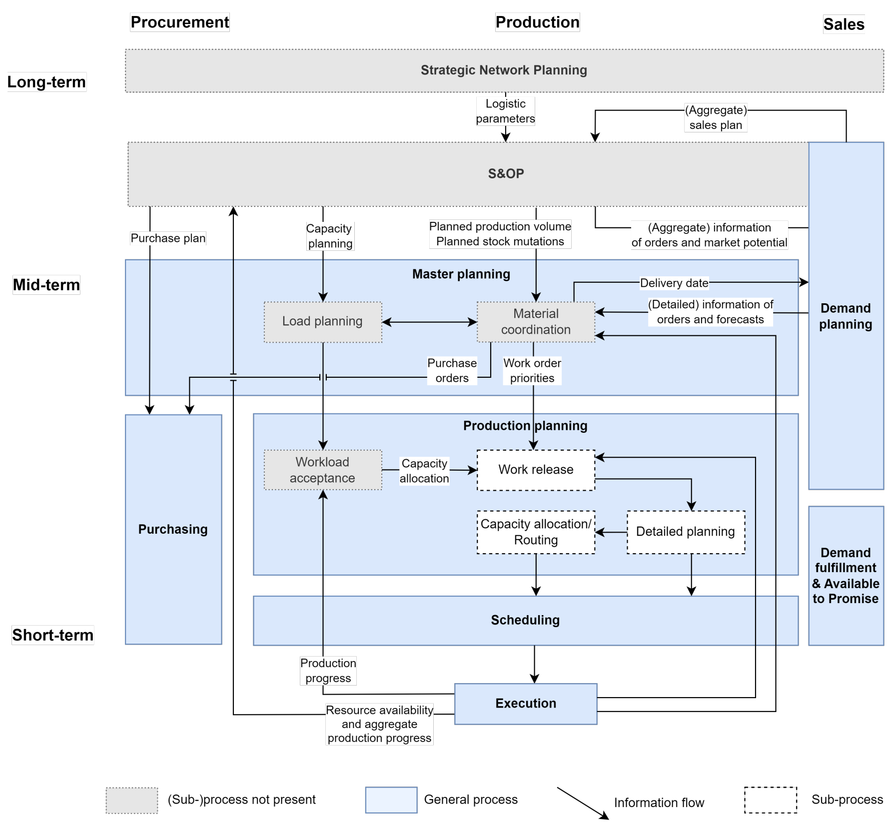


Figure 18: Integrated SCP framework applied at PT

4.2 Material coordination

A case at PT is provided in order to illustrate the difference between a planning logic that neglects material availability and a material feasible planning logic. The case study is based on the case study performed by Schouten (2018) at ASML. In this case MRP-I is compared to Material Availability Planning (MAP). MAP is the algorithm proposed by de Kok et al. (2005). This case study uses the tool developed for the implementation of the MAP logic at Philips Semiconductors (de Kok et al., 2005). This tool has been used for over seven years in practice. In Figure 19, the MRP-I planning concept is shown, and in Figure 20 the contrained-based planning concept is presented. The MRP-I planning concept starts with a sales plan, which is input for the MPS. The MPS is in turn input for MRP-I. This differs from MAP, in which the sales plan is directly input to the planning logic (Schouten, 2018). The MRP-I approach has infeasibilities at each BOM level, while for the MAP logic only a planned backlog exists at MPS level.

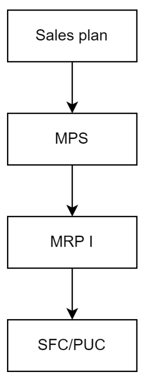


Figure 19: Concept MRP planning

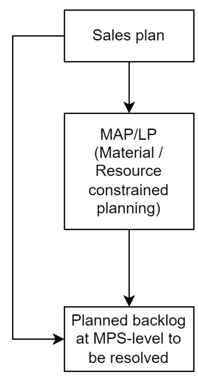


Figure 20: Concept constrained-based planning

In the case study, two end-items are assembled. The complete network is shown in Figure 21. Parameter information is shown in Table 3 and the demand forecast for week 36 till 47 is shown in Table 4. The product numbers are replaced with item A (610711016100), item B1 (610711016000), item C1 (610712007704), item B2 (610720046400) and item C2 (610721308500) for readability.

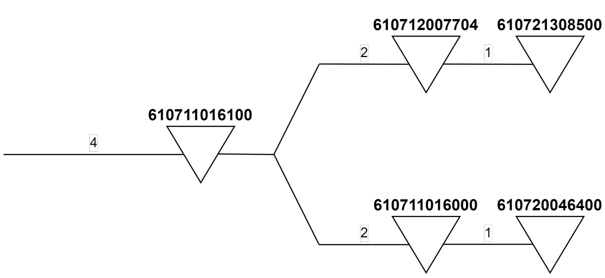


Figure 21: Network at PT including lead times

	OHS	WIP and In-Transit			
Time		37	38	39	40
610711016100 (A)	29	2	0	0	0
610711016000 (B1)	0	0	0		
610712007704 (C1)	0	0	0		
610720046400 (B2)	0	0			
610721308500 (C2)	0	0			

Table 3: OHS, WIP and In-Transit input parameters

	Demand Forecast											
Time	37	38	39	40	41	42	43	44	45	46	47	48
610721308500 (C2)	7	0	3	0	11	1	8	2	26	6	9	0
610720046400 (B2)	0	6	0	20	26	5	7	10	5	35	10	10

Table 4: Demand forecast input

As shown in Tables 4 and 5 demand equals 7 in week 37 for item C2. A net requirement of 7 is generated for all items as these items need to be replenished in the period after the lead time. The On-Hand Stock (OHS), Work in Progress (WIP) and In-Transit are zero for both the end-item (item C2) and its predecessor (item C1). Following the MRP-I logic, this results in negative OHS. At the end-product level it seems like the negative inventories are replenished after 1 week. However, this is infeasible given the negative inventories of preceding items (C1 and A). The same can be seen for demand of 6, 20 and 26 in week 38 for item B2. At end item level no negative OHS is shown. However, items B1 and A show infeasibilities. Also, MRP-I does not synchronize item order releases for the same parent item(s).

610721308500 (C2)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		7	0	3	0	11	1	8
Gross requirements		7	0	3	0	11	1	8
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	7	3	0	11	1	8
Planned on hand	0	-7	0	0	0	0	0	0
Planned orders		7	3	0	11	1	8	2

Table 5: Item 610721308500 (C2) MRP table

610720046400 (B2)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		0	6	0	20	26	5	7
Gross requirements		0	6	0	20	26	5	7
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	6	0	20	26	5	7
Planned on hand	0	0	0	0	0	0	0	0
Planned orders		6	0	20	26	5	7	0

Table 6: Item 610720046400 (B2) MRP table

610712007704 (C1)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		7	3	0	11	1	8	2
Gross requirements		7	3	0	11	1	8	2
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	0	10	11	1	8	2
Planned on hand	0	-7	-10	0	0	0	0	0
Planned orders		10	11	1	8	2	26	6

Table 7: Item 610712007704 (C1) MRP table

610711016000 (B1)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		6	0	20	26	5	7	10
Gross requirements		6	0	20	26	5	7	10
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	0	26	26	5	7	10
Planned on hand	0	-6	-6	0	0	0	0	0
Planned orders		26	26	5	7	10	5	35

Table 8: Item 610711016000 (B1) MRP table

610711016100 (A)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		36	37	6	15	12	31	41
Gross requirements		36	37	6	15	12	31	41
Scheduled receipts		2	0	0	0	0	0	0
Planned receipts		0	0	0	0	75	31	41
Planned on hand	29	-5	-42	-48	-63	0	0	0
Planned orders		75	31	41	0	0	0	0

Table 9: Item 610711016100 (A) MRP table

This shows that MRP-I does not consider child item material availability. As mentioned above, MAP does consider material availability. Tables 10, 11, 12, 13 and 14 show the unconstrained demand, gross requirements, scheduled receipts, planned receipts, planned receipts, planned OHS and planned orders for the MAP logic. In these tables it can be seen that no infeasibilities exist at lower BOM levels. Only a planned backlog is present at the MPS level as shown in Tables 10 and 11.

610721308500 (C2)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		7	0	3	0	11	1	8
Gross requirements		7	0	3	0	11	1	8
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	0	0	8	0	0	0
Planned on hand	0	-7	-7	-10	-2	-13	-14	-22
Planned orders		0	0	8	0	0	0	24

Table 10: Item 610721308500 (C2) MAP table

610720046400 (B2)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		0	6	0	20	26	5	7
Gross requirements		0	6	0	20	26	5	7
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	0	0	23	0	0	0
Planned on hand	0	0	-6	-6	-3	-29	-34	-41
Planned orders		0	0	23	0	0	0	51

Table 11: Item 610720046400 (B2) MAP table

610712007704 (C1)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		7	3	0	11	1	8	2
Gross requirements		0	0	8	0	0	0	24
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	0	8	0	0	0	24
Planned on hand	0	0	0	0	0	0	0	0
Planned orders		8	0	0	0	24	26	6

Table 12: Item 610712007704 (C1) MAP table

610711016000 (B1)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		6	0	20	26	5	7	10
Gross requirements		0	0	23	0	0	0	51
Scheduled receipts		0	0	0	0	0	0	0
Planned receipts		0	0	23	0	0	0	51
Planned on hand	0	0	0	0	0	0	0	0
Planned orders		23	0	0	0	51	5	35

Table 13: Item 610711016000 (B1) MAP table

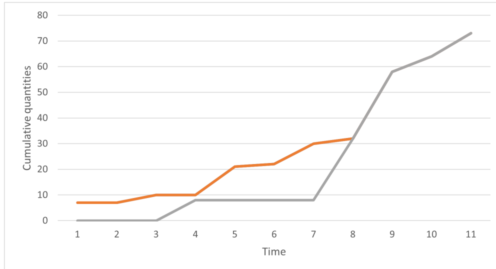
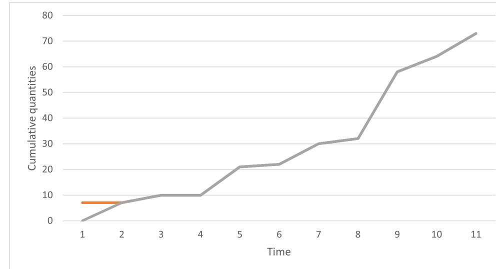
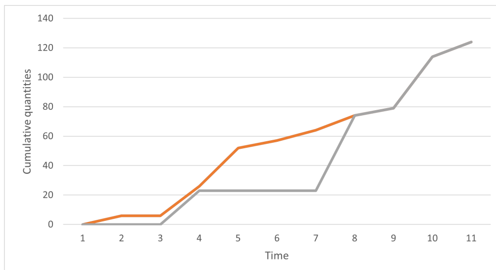
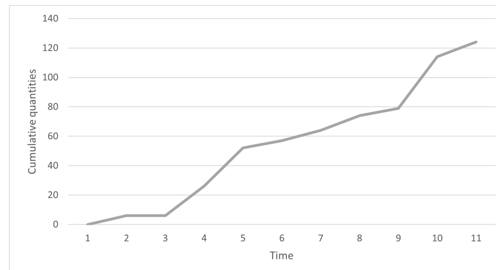
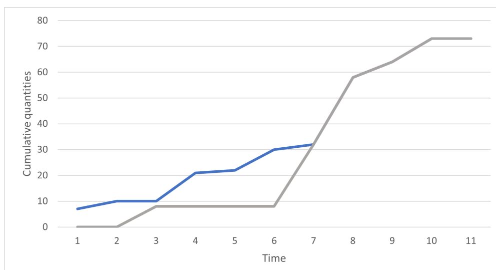
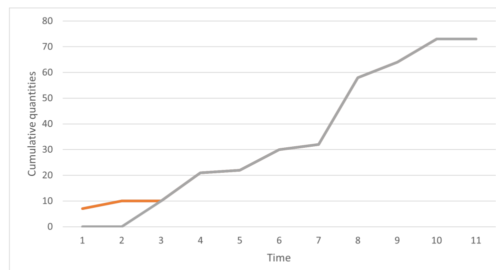
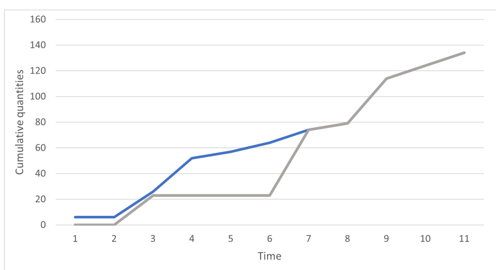
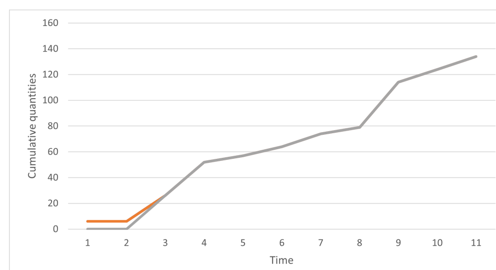
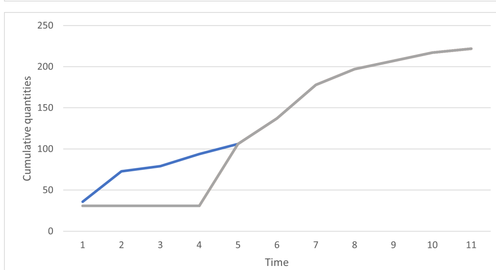
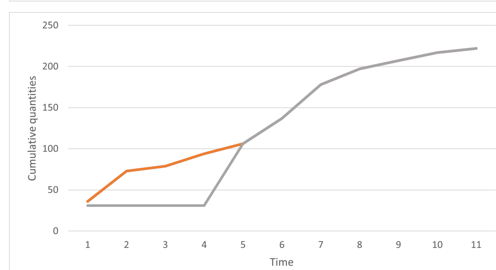
610711016100 (A)	wk 36	wk 37	wk 38	wk 39	wk 40	wk 41	wk 42	wk 43
Unconstrained demand		36	37	6	15	12	31	41
Gross requirements		31	0	0	0	75	31	41
Scheduled receipts		2	0	0	0	0	0	0
Planned receipts		0	0	0	0	75	31	41
Planned on hand	29	0	0	0	0	0	0	0
Planned orders		75	31	41	19	10	10	5

Table 14: Item 610711016100 (A) MAP table

When Tables 10, 11, 12, 13 and 14, created using MAP, are compared to the Tables 5, 6, 7, 8, 9 obtained using MRP-I, the effect of taking material availability into account can be seen. Table 15 provides an overview of the supply and demand plan for the MRP-I and MAP logic to compare both results. The "MAP" column shows the supply and demand plan for each item obtained using the MAP algorithm described by de Kok et al. (2005). The "MRP" column shows the supply and demand plan created using MRP-I for each item. In the graph, the cumulative unconstrained demand, cumulative demand and cumulative deliveries are shown. Cumulative unconstrained demand is the translated end-item demand, taking into account lead times, scheduled receipts and OHS. Cumulative demand are the gross requirements of an item, derived from the number of items required by the succeeding item(s) (Schouten, 2018).

It can be seen that item A faces shortages till period t = 5 in both the MRP-I and MAP column. The lead time of item A is t = 4. This indicates that supply catches up with demand after 4 periods as shown in the MRP-I and MAP column, given that it is modelled as an item with an external supply source. In the MRP-I column, the unconstrained demand is equal to the demand. Item B1 shows shortages during the first two periods. In the MRP-I graph it seems like supply catches up after two periods (given lead time 2). MAP generates a different plan as it takes material availability into account. Using the MAP method, the cumulative demand is equal to the cumulative supply for item A. For item B1, the cumulative demand is equal to the supply capacity of item A. The cumulative unconstrained demand shows what is needed to avoid shortages. The lead time of item A is 4, so cumulative supply catches up with the cumulative unconstrained demand after 4 periods. For item B1, the cumulative demand is equal to the cumulative supply. Given the shortages at the preceding item A, supply can only catch up after 6 periods (the lead time of both items B1 and A). For item B2, the cumulative unconstrained demand is equal to the cumulative demand as it is an end item. For this item the cumulative supply shows what can be supplied from the preceding item B1. Using the MAP method, the cumulative supply catches up with demand after 7 periods (lead times of item B2, item B1 and item A combined). For the MRP-I method, it seems as if there are no shortages for item B2 even though this cannot be realized. The MAP shows the shortages at end item level. For items C2, C1 and A, the same pattern can be observed. Therefore, this small case study shows that the MRP-I plan is not feasible.

One important aspect of taking material availability into account is the allocation policy. The allocation policy distributes the available items. In the example, it can be seen that the planned OHS for item A is 29 in week 36. Since the unconstrained demand in week 37 is 36 with scheduled receipts equal to 2, not all unconstrained demand can be satisfied. The tool uses the Rounded consistent appropriate share with run-out time leftovers (RCRO) policy to allocate the available items. Allocation policies including the RCRO policy are described in further detail by Schouten (2018).

Item	MAP	MRP
610721308500 (C2)		
610720046400 (B2)		
610712007704 (C1)		
610711016000 (B1)		
610711016100 (A)		

Cumulative unconstrained demand — Cumulative demand — Cumulative deliveries

Table 15: Supply and demand plan using MAP and MRP at PT

4.3 Proposed master planning processes

This section describes the proposed master planning processes and is part of the "Design master planning processes" step of the regulative cycle. The master planning processes are modeled in compliance with the needs and constraints indicated by stakeholders at PT using ArchiMate. The processes are structured using time (horizontally) and hierarchy (vertically). For some business functions and processes, it is relevant to provide more information than offered by the functionalities of ArchiMate. For example, when modeling the business function "creation of planned orders" it can only be seen that ProductLocation is used as a data object in ArchiMate. However, in IDEF0 it becomes clear that an attribute of ProductionLocation, such as OHS, is input and the attribute lead time is control. Therefore, IDEF0 is chosen as an additional technique to model "creation of planned orders" as IDEF0 provides more details regarding input, output, controls and mechanisms. Together these techniques provide an overview of the processes including input, output, application components, controls, data and actors.

Figure 22 shows the actors relevant for the master planning processes at PT. The relevant actors for the processes are demand planners, production planners, a master planner and the purchasing department. A data model is also visualized using ArchiMate. Given that this is the same model as shown in Figure 5 (Section 1), the model in ArchiMate is presented in Appendix G for completeness.

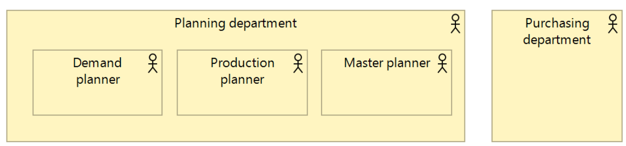


Figure 22: Actors relevant for SCP at PT

Figure 23 shows the general supply chain planning process. This is the SCP process as derived from section 3 with time and hierarchy taken into account. This process starts with strategic network planning, which has a frequency of once per year. Strategic network planning focuses on supply chain configuration, which includes the type of products to produce, the markets to be served and the (sizes of) locations to be used for production. The flow relation is used to transfer information and decisions made in the strategic network planning process to the next process. The following step in the SCP process is demand planning. This includes generating forecast scenarios, which will be used in the S&OP process. S&OP has a frequency of once per month and includes the creation of aggregated planning scenarios. The S&OP process results in a S&OP sales plan in which it is established what the company wants to produce and sell. This sales plan is again transferred to the next process as shown by the flow relation. Next, the demand planning process results in a demand plan. This demand plan is aligned with the S&OP sales plan and takes operational constraints into account. This process occurs monthly and results in a gross forecast. The next step in the SCP process is order management, where the sales orders and forecast information are outcomes. Furthermore, an ATP check is performed for sales order delivery date promising. The sales order and forecast information is used by the master planning process. This is a weekly process in which planned orders and purchase requisitions are generated and the backlog at MPS level is addressed. The purchase requisitions are input for the purchasing process and planned orders are input for production planning. In production planning the planned orders become production orders after a material and capacity check. Finally, the orders are scheduled and released for execution. Given the focus of this project, the master planning process is visualized and described in more detail. When the process consists of more layers, an indicator is used after the name of the process to refer to the higher or lower level process.

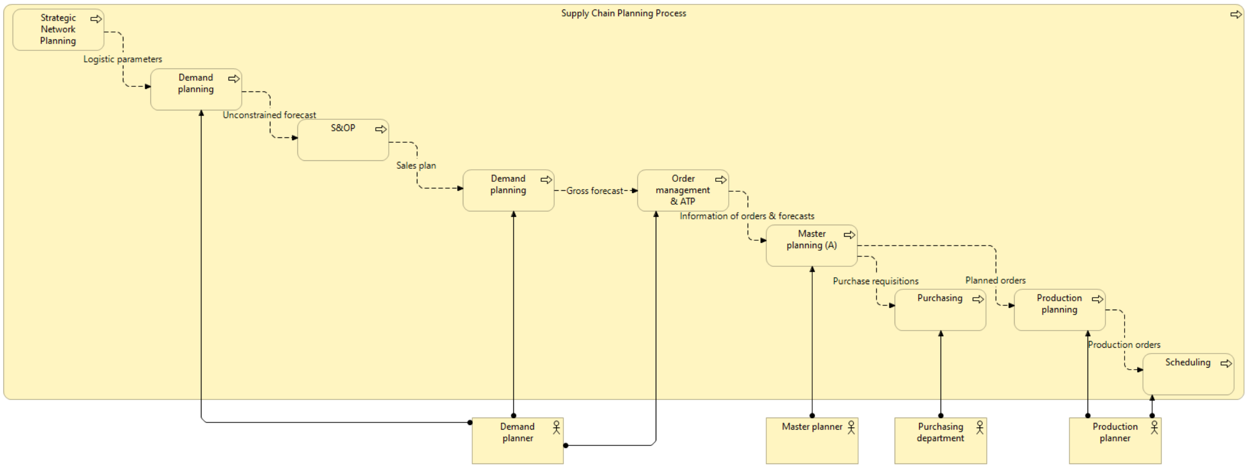


Figure 23: Proposed SCP process at PT using ArchiMate

Figure 24 shows the master planning process created using ArchiMate. The process starts with the creation of planned orders using the system, which is described in more detail in Figure 25 using IDEF0. The sales orders and forecasts are input together with OHS, purchase orders, purchase requisitions, planned orders and production orders. It is important to note that the logic takes material and capacity availability into account. This eliminates the processes where the planning and purchasing department are solving infeasible planned orders at all Bill of Material levels. Furthermore, batch size has a standard and minimum value. A value lower than the standard value is used when the planned order is later than the date of the sales order. When planned orders are created while taking material and capacity constraints into account in APS, it can result in planned orders after the allocated sales orders. To solve this the process "Solve planned orders later than allocated sales order" (B1) should be followed, which can result in firmed planned orders. This means that the planning logic does not automatically change this order until it is unfirmed by a planner. To check whether the firmed planned orders are still feasible, the "check firmed orders (B2)" process should be executed. Both processes are described in more detail below.

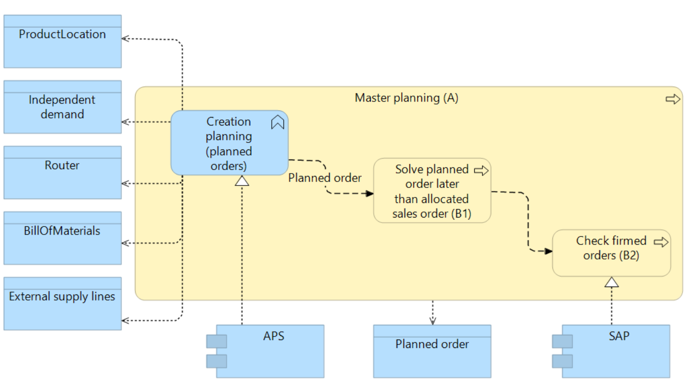


Figure 24: Master planning using ArchiMate

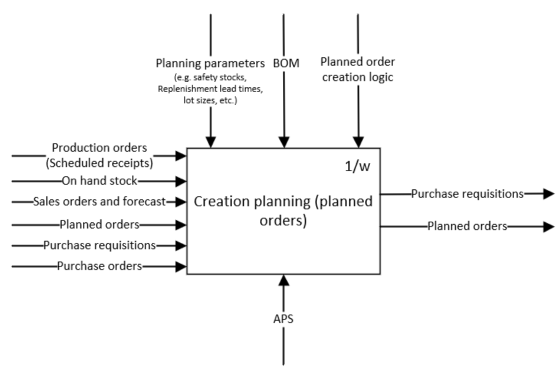


Figure 25: Planned order creation using IDEF0

First of all, the "solve planned order later than allocated sales order (B1)" process is described and shown in Figure 26. This process is executed at MPS level and includes backward pegging. Backward pegging is a functionality that is also part of the MAP tool and can be used in this process. An unfirmed planned order can be later than a sales order when it takes more time to execute an order than time till due date. This process is described in Figure 26 as "time needed for order execution is larger than the time till due date (C1)". Furthermore, a planned order finish date can be later than the allocated sales order due date when there is not enough capacity available. This is displayed as "Not enough capacity (C2)". The last possible cause of a planned order after a sales order is when the supply of one or more materials is expected to be later than needed for the sales order. This is referred to as "delivery materials later than needed for sales order (C3)". It is possible that only one of these issues is applicable to the situation. In this case, only the applicable process will be executed and triggered. This is indicated with the business event in the sub-processes. However, it can also be the case that a combination of issues is applicable to the situation. For example, a planned order can be later than a sales order due to limited material availability and limited capacity. Some issues are easier to solve than others. This determines the order of the processes C1, C2 and C3 shown in Figure 26. The "time needed for execution is larger than the time till due date (C1)" is relatively easy to check. Therefore, C1 is positioned first in the process. Dealing with limited capacity is considered before limited materials as additional communication with the purchasing department might be necessary to deal with limited materials. Also, the analysis of limited materials can be more extensive due to the multi-layered BOMs. For each case, the process is described in more detail in Figures 27, 28 and 29.

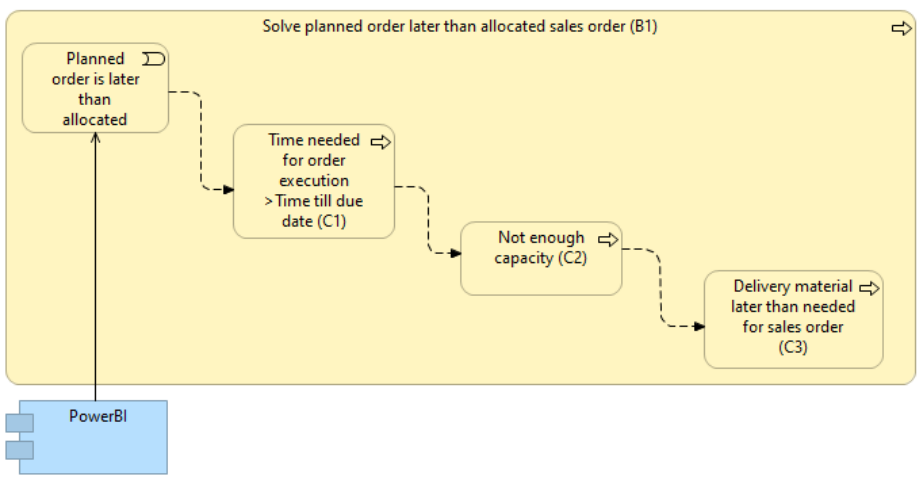


Figure 26: Solve planned order later than allocated sales order (B1)

First of all, in the "solve planned order later than allocated sales order (B1)" process it can occur that a planned order is later than a sales order, because the time needed to execute an order is more than the time till due date (C1). When this occurs, it should be checked by the master planner whether the batch size can be decreased below the minimum batch size. The analysis should be thorough and includes checking logistical constraints and impact on PT. If decreasing the batch size does not solve the issue, the sales order has to be delayed. This process is shown in Figure 27

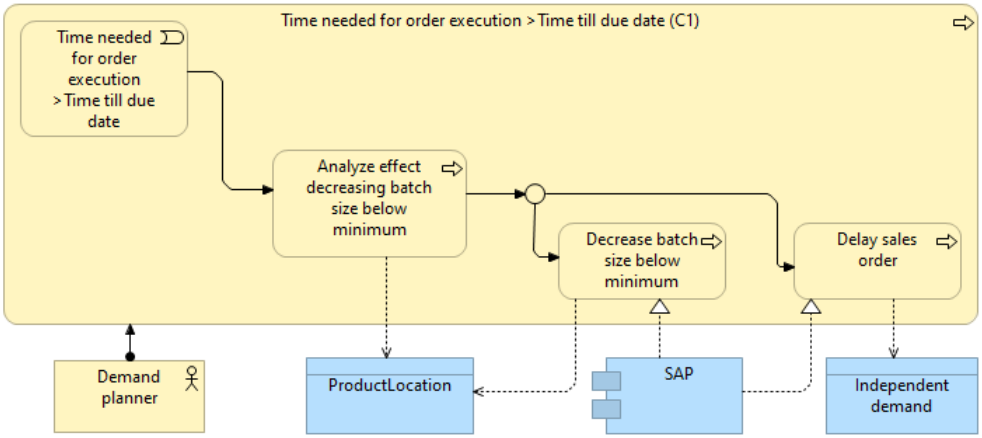


Figure 27: Time needed for order execution is larger than time till due date (C1)

Secondly, the planned order can be planned on a later date than the sales order due to the lack of capacity (C2). In this case it should first be checked whether decreasing the batch size has a significant impact. Also, the consequences should be analyzed as discussed above for process C1. If the reduction of the batch size has an insufficient effect, the consequences of using capacity allocated to other orders should be analyzed. Based on this analysis, the master planner decides if the capacity allocated to other orders will be used. It is important to realize that using the capacity allocated to other orders has an impact on all related orders in the planning. If the capacity will not be used, the sales order needs to be delayed by the demand planner. The process is shown in Figure 28.

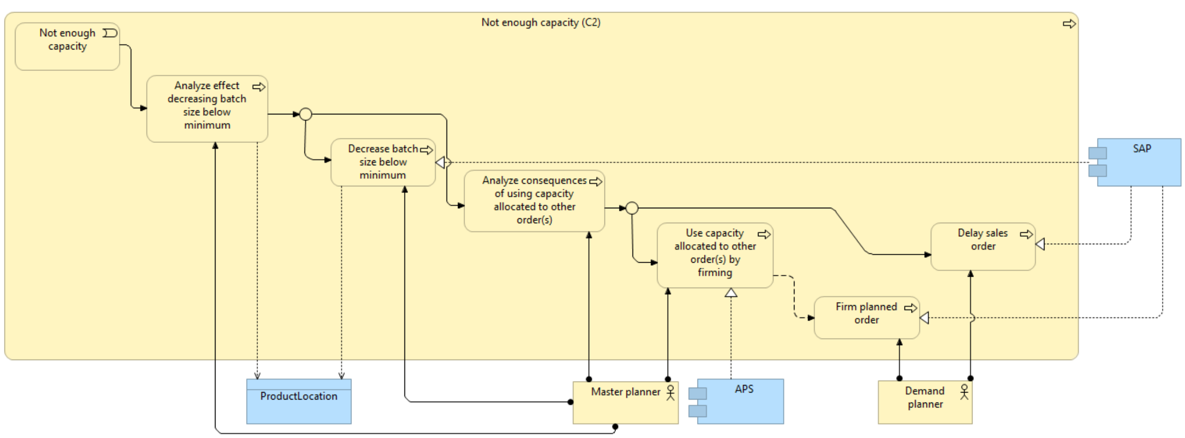


Figure 28: Not enough available capacity (C2)

Lastly, the planned order can be later than the allocated sales order when the delivery of one or more materials is expected to be later than needed for the sales order. This is referred to as "delivery materials later than needed for sales order (C3)". Material availability is taken into account in the new logic that creates planned orders. Figure 29 shows all possibilities for PT to solve the backlog at MPS level when dealing with limited material availability. The options are split into smaller processes for readability. Below each option is discussed in detail.

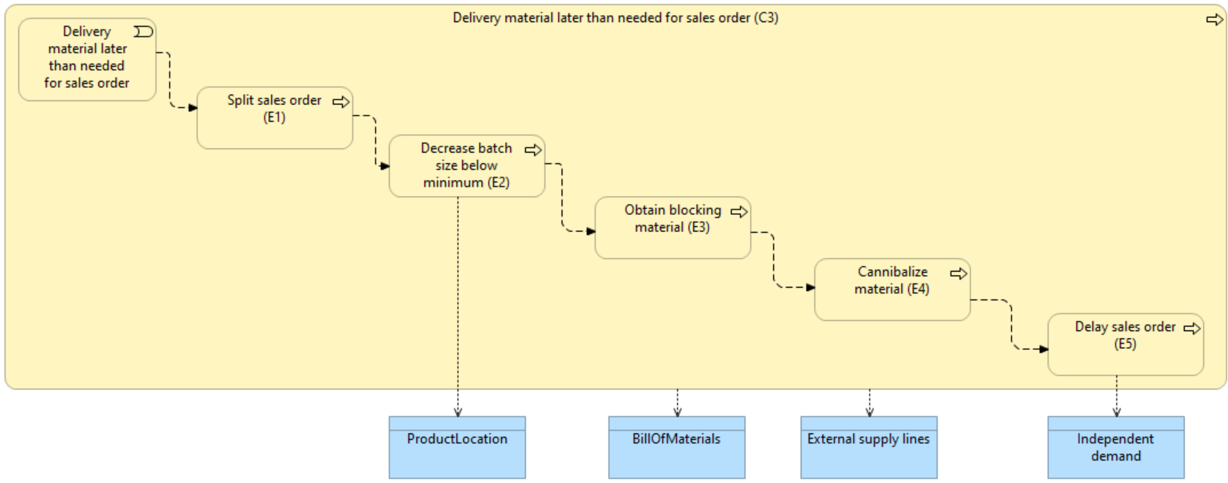


Figure 29: Delivery material later than needed for sales order (C3)

When dealing with blocking materials it should first be checked whether it is possible to split the sales order (E3). The customer agreements should be checked or it should be discussed with the customer. If it solves the issue the sales order should be split by the demand planner. This is shown in Figure 30. Next, it can be considered to decrease the batch size. This is similar to the process described for C2 and shown in Figure 31

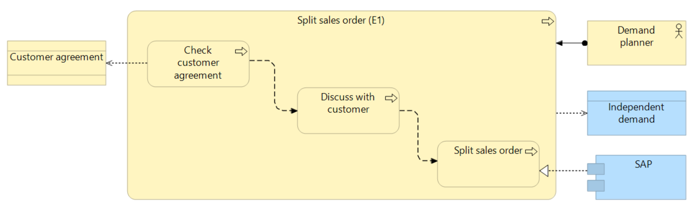


Figure 30: Split sales order (E1)

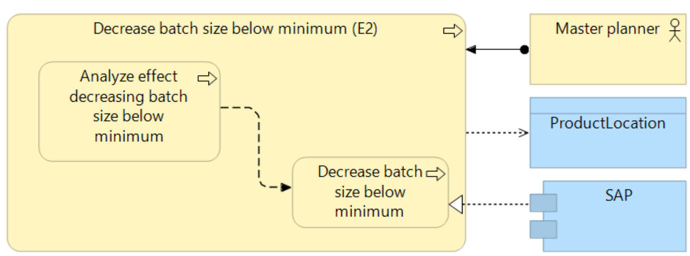


Figure 31: Decrease batch size (E2)

Next, it might be possible to expedite supply (Figure 32. The master planner first checks whether it is possible to prepone the planned order given other materials and capacity necessary to complete the order. It might be possible to expedite the supply of the current critical path of the planned order such that the sales order date is reached. However, by expediting this supply date, another material in the BOM may become the new critical path and also for this material it has to be checked whether it can be preponed. This check is crucial when expediting supply and moving planned orders to an earlier date and executed by preferably one (or more depending on the workload) master planner. If it is possible to move the order given all other materials and available capacity, the master planner will prepone and firm the planned order. Next, the demand planner contacts the purchasing department to expedite the blocking material. If the purchasing department manages to expedite supply, they should change the data. Given that the order is firmed, it should be checked regularly. This happens in the process "check firmed orders (B2)".

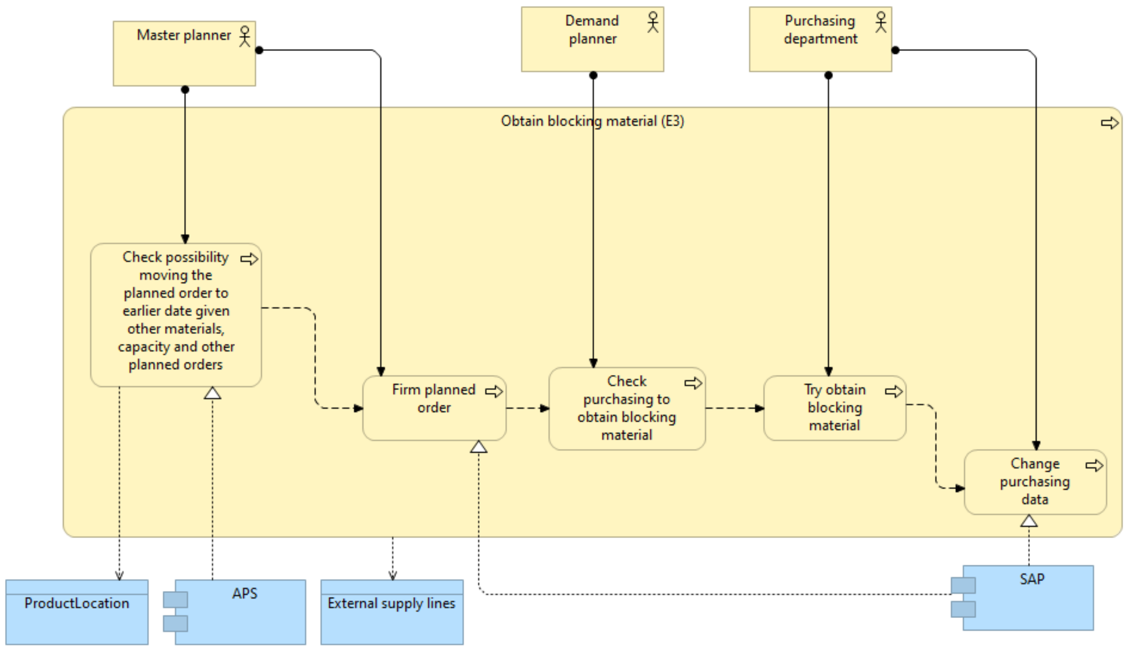


Figure 32: Expedite blocking material (E3)

The last option to obtain materials which arrive later than needed is to "cannibalize materials (E4)" (Figure 33). When a material is used from another order, that other order will be delayed as a result. That means that this process should be highly exceptional and priorities should be clear as it will be a deviation from the default prioritization. The planned orders has to be firmed if the materials are cannibalized, which means that the order needs to be checked manually.

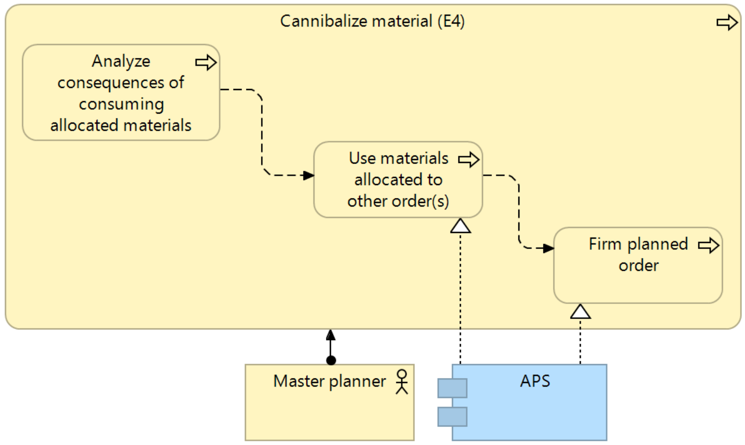


Figure 33: Cannibalize blocking material (E4)

As mentioned before, a firmed planned order needs to be checked manually. This process is shown in Figure 34. It should be checked whether the reason that the order is firmed after the allocated sales order is valid. The sales order should be delayed in case of a valid reason and unfirmed otherwise. Another reason to review firmed planned orders is that material availability can be too optimistic. A firmed planned order will not be moved automatically to a later date when the supply is not present or confirmed in a certain time horizon, which means that firmed planned orders can be infeasible. This indicates that it should be checked by the demand planner whether the order is still feasible.

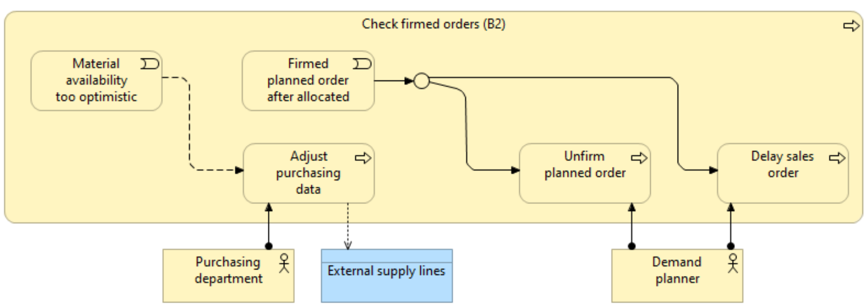


Figure 34: Check firmed orders (B2)

This section describes the master planning processes given the needs and constraints formulated by stakeholders at PT. That indicates that certain parts of the process are modelled according to the preferences of PT. In the next section the processes are evaluated.

5 Application and Evaluation

The application and evaluation section consists of two parts. First of all, the master planning processes are created taking the needs and constraints of PT into account. Therefore, modeling decisions have been based on input from stakeholders. It is important to evaluate these decisions as they might not result in an ideal process. Secondly, it is described how the SCP framework is used to design the master planning processes at PT including a description of the face validity based on input from stakeholders. This is the last step of the regulative cycle.

5.1 Evaluation master planning process PT

Firstly, the highest level process defined for PT is evaluated. The SCP process in Figure 23 is structured using hierarchy and time. The process still shows aspects of the SCP framework based on literature. When it is structured using hierarchy and time, some processes appear to occur twice. These processes are executed at different points in time and at a different aggregation level. Therefore, the proposed process at PT is a visualization of the actual process flow with additional information. The SCP process at PT does not present the frequency of each decision, although this would be valuable information.

Secondly, the master planning process can be seen in Figure 24. In this process, planned orders are created using a logic. Therefore, the result of the master planning process depends on this logic. As established in section 4, the material and capacity availability needs to be taken into account to address the problems at PT. This is also confirmed by Wiers and de Kok (2017) and Schouten (2018). PT has not created the logic yet, which means that the process can change too as the output changes depending on the logic used to create planned orders. This also shows the relevance of a planning logic.

Also, it is important to consider the process of firming a planned order. As soon as orders are firmed they will not be adjusted by the system, which means that these orders need to be checked manually (Bertrand et al., 1990). This indicates that it is important to avoid these scenarios and analyze when planned orders will be firmed by the planner. Figure 35 shows the incoming business relations of the firmed planned order process. On the right, the processes that precede the "firmed planned order" process are displayed. It can be seen that the "use materials/capacity allocated to other order(s)" process results in firmed planned orders. Firming means that the date is adjusted and fixed. This is different than changing the allocation of materials. In the MAP tool, it is checked whether it is possible to change the proposal of planned orders to change the allocation of materials. However, when the proposal is changed, infeasibilities arise in the tool which indicates that the whole proposal needs to be recomputed and it is not possible to change the proposal and take material availability into account. The last process that is related to firming a planned order is expediting supply (E3). After the master planner confirms that it is possible to move the planned order, given the availability of other materials and capacity, the order needs to be firmed. PT should focus on minimizing the cases where planned orders are firmed as they imply more manual work. Furthermore, it has consequences for other related production and planned orders.

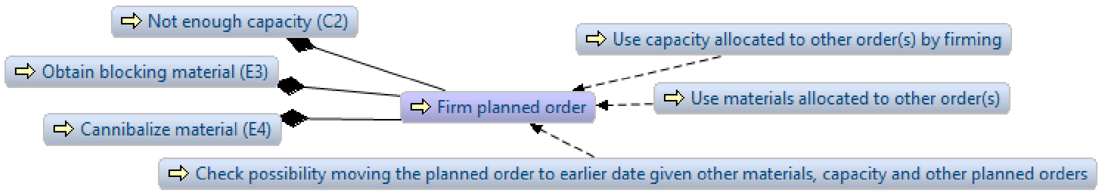


Figure 35: Firmed incoming business process relations

Furthermore, PT wants to have the option to use materials that are allocated to other orders. However, changing the allocation of materials last minute does not result in a better planning. Instead, it results in less stability and more manual work. De Kok and Visschers (1999) show that pre-allocation policies perform quite well compared to allocation policies where common components are distributed at the latest possible moment, both with respect to costs and service. Therefore, cannibalizing materials should be exceptional and needs thorough analysis instead of myopic decision-making.

The process of expediting supply seems straightforward as presented in Figure 32. However, this process contains many communication lines and loops. The purchasing process is not part of the scope of this thesis, yet it is crucial for a successful planning process.

Lastly, the variability regarding time is high. For example, in Figure 32 it is checked whether it is possible to move the planned order to an earlier date given other materials and capacity. The analysis needs to be thorough, but the process times vary a lot. As a result, it is difficult to show the duration of processes in the visualizations.

This section evaluates the proposed master planning process for PT. Based on the processes, evaluation and design step, the final SCP framework can be evaluated. This is described in the next section.

5.2 Evaluation SCP framework

In this section, the SCP framework derived from literature is evaluated using the proposed master planning processes. The first evaluation aspect is the usage of hierarchy and time to structure the processes. The usage of the natural hierarchy (Wiers & de Kok, 2017) shows the order and hierarchical level of processes. This is applied to the SCP framework. Besides hierarchy and time, swimlanes are used to provide more information regarding the actors responsible for the processes. The swimlane view cannot be combined with the hierarchical view as the swimlane view does not have to match the hierarchical aspect. The final swimlane framework can be seen in Figure 37 and the final framework using hierachy is shown in Figure 36.

More adjustments have been made to this framework based on the evaluation and application of the master planning processes at PT. First of all, the frequency of processes is added to the framework on the top right of the process. It can be seen that strategic network planning and demand planning have a frequency of once per year. Furthermore, S&OP and demand planning occur monthly and order management and master planning weekly. Purchasing, production planning and scheduling is a daily process.

Besides the frequency of processes, some additional input and output has been modeled. This includes gross forecast as the output of demand planning and input of order management. Furthermore, planned orders are output of the master planning process and input for production planning. In production planning the orders are converted to production orders.

The majority of the MRP-II framework is not displayed in the final framework since it is not recommended to structure the planning process using this framework. The MRP-II framework does not create a material and capacity feasible plan. In MRP-II CRP results in manual adjustments to the planning using firmed planned orders. As mentioned in section 5, firmed planned orders should be avoided. Therefore, it is recommended to take load planning into account in the planning logic. Furthermore, MRP-I and MPS are not shown in the model. Given the shortcomings of MRP-I it is recommended to use a logic that takes material and capacity availability into account when creating planned orders. This should be covered by the material coordination and load planning process. This results in the SCP framework shown in Figure 36.

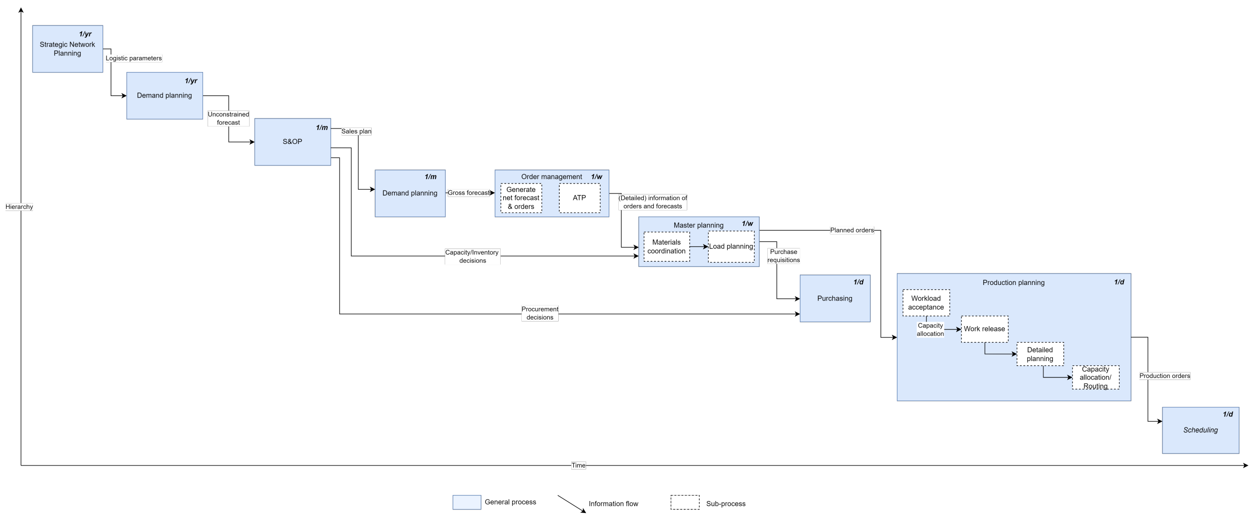


Figure 36: Final SCP framework structured using hierarchy and time

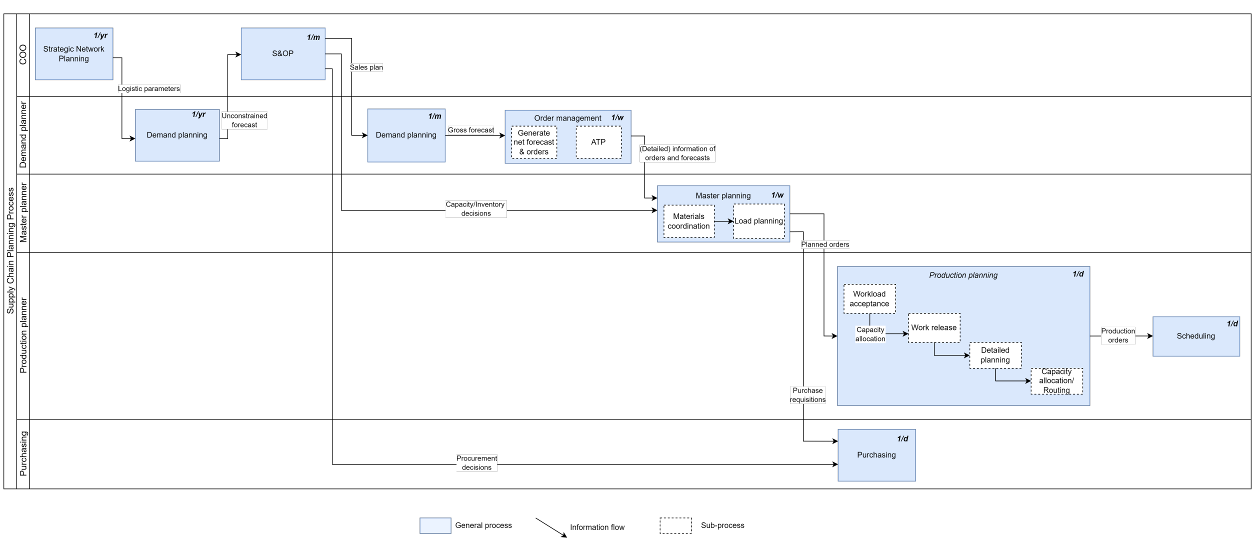


Figure 37: Final swimlane SCP framework

5.3 Reflection

The designed SCP framework is used by PT to create an overview of the SCP processes and structure the master planning processes. This reflection is part of the last step of the Design Science Research Methodology and includes a face validation of three main stakeholders related to the master planning process. The APS Architect at PT mentions: "Supply Chain Planning frameworks are essential for our process definitions and improvements across different related domains at Prodrive Technologies. Structure and overview are rapidly missing due to our complex, vertically integrated supply chain which differs from traditional supply chains and thus conventional frameworks are not applicable. This well-defined framework allows us to quickly identify dependencies (e.g. competences, data and tools) which provides both an excellent start- and endpoint for change analysis". The problem owner agrees and stresses that the framework supports the definition of clear requirements for the design of master planning processes. He mentions: "It shows that a fundamental change is necessary to improve planning. This framework allows PT to see the whole picture and make structural adjustments." The demand planning process owner also emphasizes that it is a valuable framework to get an overview. The framework enables alignment between stakeholders, is a convenient starting point and helps to structure the master planning processes.

Based on the face validation, the SCP framework seems to be valuable for PT to gain an overview and structure the processes. As mentioned in section 1, PT can be classified as an A-plant category using the V-A-T classification described by Umble (1992). That means that for other companies characterized by convergent assembly points throughout the production process, it is expected that the SCP framework can be applied. Furthermore, PT works according to common concepts such as SAP as ERP. This indicates that the framework is widely applicable.

6 Conclusion and Discussion

6.1 Conclusion

This thesis focuses on the design of a SCP framework to support the design of supply chain processes related to master planning. A comprehensive and structured overview of the master planning processes remains to a large extent unaddressed in literature, even though this is crucial for the design of master planning. Therefore, a SCP framework is created. The SCP framework is presented in Figure 36 and applied and evaluated at the manufacturing company PT by modeling detailed master planning processes.

The framework starts with Strategic Network Planning, which occurs once every year. The process focuses on supply chain configuration, which includes the type of products to produce, the markets to be served and the (sizes of) locations to be used for production. Logistic parameters are the output of Strategic Network Planning and input for Demand planning. Demand planning includes the generation of forecast scenarios and results in unconstrained forecast which will be used in the S&OP process. Demand planning and S&OP also have a frequency of once every year. The S&OP process results in a S&OP sales plan in which it is established what the company wants to sell and make. Next, the Demand Planning process results in a demand plan. The demand plan is aligned with the S&OP sales plan and takes operational constraints into account. The process occurs monthly and results in a gross forecast. The gross forecast is input for order management and ATP. This is a weekly process in which sales order delivery dates are promised and sales order and forecast information is generated. This information is used in the master planning process. This is a weekly process in which planned orders and purchase requisitions are generated and the backlog at MPS level is addressed. The purchase requisitions are input for the purchasing process and planned orders are input for production planning. In production planning the planned orders become production orders after a material and capacity check. Finally, the orders are scheduled and released for execution. The framework provides an overview of SCP, which is crucial for the successful implementation of master planning processes and other processes related to SCP.

The SCP framework is evaluated using a case at the manufacturing company PT. To evaluate the SCP framework with a focus on master planning the master planning processes are modeled in detail. The master planning processes depend on the logic, needs and constraints at the company. In practice often MRP-I is used to generate planned orders, which is also the case at PT where MRP-I is associated with planning instability. One of the causes of planning instability is related to the infeasibilities created by MRP-I. These infeasibilities are created because MRP-I does not consider material and capacity availability. To illustrate the effect of taking material availability into account, MRP-I is compared to MAP. MAP only shows a backlog at MPS level and creates a material feasible planning. Therefore, a logic should be used that takes material availability into account. Based on a material feasible logic and the SCP framework, the detailed master planning processes are described. These can be used to support the design of master planning. Therefore an answer to the research question: "How can the design of master planning processes using APS at PT be supported by a supply chain planning framework?" is provided.

6.2 Recommendations

It is recommended to use the SCP framework shown in Figure 36 to design SCP processes including Strategic Network Planning, Purchasing, Demand Planning, Production Planning, Scheduling, Order Management and Master Planning. To deal with planning instability established in research and at PT, it is recommended to take material and capacity availability into account. This entails that the planning logic creates a material and capacity feasible planning. MAP takes material availability into account and creates feasible planned orders. Therefore, MAP or any other material feasible logic is recommended to be used.

6.3 Contribution to literature

The SCP framework designed in this thesis contributes to literature as a comprehensive and structured overview of the master planning processes remains to a large extent unaddressed. Some SCP frameworks are presented in literature and identified using a systematic literature review. These frameworks include the MRP-II framework, production control model and APS modules based on the SCP matrix. Some aspects of these frameworks do not result in the most efficient process. This is different from the SCP framework created in this project. Furthermore, the frameworks retrieved from literature do not show the entire SCP process including inputs, outputs, roles, hierarchy and time. In the integrated and evaluated SCP framework designed in this research, these aspects are modeled and can be used to structure complex planning processes in literature and practice.

The other contribution to literature, besides the SCP framework, is the confirmation of the master planning problems in practice. Planning instability due to MRP-I is established at PT and in literature. Furthermore, additional stock, increased costs and low planning efficiency are all described in literature as consequences of planning instability and identified at PT. This confirmation from practice can be seen as a contribution to literature.

6.4 Contribution at PT

The SCP framework is a valuable framework to structure planning processes in companies dealing with complex planning challenges. The SCP framework can help to design processes with a focus on master planning. PT requires an effective master planning process. An overview is needed to enable the successful design and implementation of a planning logic and master planning processes,. This overview is provided using the SCP framework proposed in this thesis. Furthermore, detailed master planning processes are modeled for PT. The SCP framework and detailed master planning processes are already being used by PT to design the master planning processes. Not only do they initiate the discussion on how to structure the planning processes, they are also used as input on how to structure it. Often assumptions and simplifications are made in literature to solve the problem, which makes it ineffective in practice. However, the objective of this project is to provide an overview of master planning and the related SCP concepts with the aim to use it in both literature and practice. Given that the result of this project is already being used in practice, it is shown that this project is of significant value for PT and other companies dealing with similar planning problems.

6.5 Limitations

This research has several limitations, which are important to discuss. First of all, capacity availability is not illustrated using MAP even though this causes instabilities in the planning at PT. In the detailed master planning processes it is assumed that capacity availability is taken into account. However, this has not been analyzed in as much detail as material availability. Second, the effect of changing the proposal of planned orders to adjust the allocation of materials can not be simulated using the MAP tool. This is a requirement of PT. However, the effect is not analyzed in this project. Third, the detailed master planning processes depend on the type of logic and circumstances. That means that the detailed master planning processes modeled in this thesis cannot be applied to other companies. However, they can be used as a guideline and additional insight for companies to design their detailed master planning process. Lastly, the SCP framework is based on input from the problems related to master planning. However, distribution and transportation are also part of the APS modules and SCP matrix. Also, purchasing plays a crucial part in an efficient master planning process as purchasing provides lead time input. When it is unclear when supply arrives it will be impossible to take material availability in the planning logic. Therefore, purchasing is a crucial process for master planning. Given the scope of this project, the purchasing process is not analyzed. However, the purchasing processes should be analyzed, efficiently designed and implemented for a successful master planning process.

6.6 Future research

Four directions for future research are proposed. First of all, the effect of changing the allocation of supply of planned orders cannot be examined using the MAP tool. This tool has been used for multiple years at Philips Semiconductors (de Kok et al., 2005). However, this aspect has not been investigated yet. Even though this is desired in practice as indicated by PT. Therefore, it would be valuable to take this aspect for further development of the tool. Secondly, an important aspect of considering material availability in the planning logic is the allocation policy. The allocation policy distributes the available items. The tool uses the RCRO policy to allocate the available items. Allocation policies including the RCRO policy are analyzed by Schouten (2018) in a low-volume environment at ASML. It would be very valuable to analyze which policy would be best for PT using a similar approach as Schouten (2018). Thirdly, capacity availability is not taken into account by MAP. Even though capacity is not identified as a major bottleneck compared to material availability, it is still interesting to analyze the effect of capacity availability. The result can also have an effect on the detailed master planning processes. Lastly, the focus of this project is master planning. However, more aspects have been identified in the SCP matrix. Therefore, it would be interesting to conduct similar research related to the processes Strategic Network Planning, Purchasing, Order Management, Production Planning, Scheduling, Transport planning, Distribution Planning and Demand Planning. This might reveal more insights into SCP and the dependencies between processes.

References

Archimate (version 4.10.0) [Computer software]. (2022). Retrieved from `https://www.archimatetool.com`

Bertrand, J., Wortmann, J. C., & Wijngaard, J. (1990). *Production control: a structural and design oriented approach.* Elsevier Science Inc.

Blackburn, J. D., Kropp, D. H., & Millen, R. A. (1986). A comparison of strategies to dampen nervousness in mrp systems. *Management science*, *32*(4), 413–429.

de Kok, A. G., Janssen, F., Van Doremalen, J., Van Wachem, E., Clerkx, M., & Peeters, W. (2005). Philips electronics synchronizes its supply chain to end the bullwhip effect. *Interfaces*, *35*(1), 37–48.

de Kok, A. G., & Wiers, V. C. (2016). *Functional design of an aps system [class handout].* Eindhoven University of Technology, Course: 1CM150.

De Kok, T. G., & Visschers, J. W. (1999). Analysis of assembly systems with service level constraints. *International Journal of Production Economics*, *59*(1-3), 313–326.

Fleischmann, B., & Meyr, H. (2003). Planning hierarchy, modeling and advanced planning systems. *Handbooks in operations research and management science*, *11*, 455–523.

Gregor, S., & Hevner, A. R. (2013). Positioning and presenting design science research for maximum impact. *MIS quarterly*, 337–355.

Hayes, R. H., & Clark, K. B. (1985). Explaining observed productivity differentials between plants: Implications for operations research. *Interfaces*, *15*(6), 3–14.

Heisig, G. (2002). *Planning stability in material requirements planning systems.* Springer Science & Business Media.

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. *MIS quarterly*, 75–105.

Mather, H. (1975). *Reschedule the reschedules you just rescheduled: way of life for mrp?* George Plossl Educational Services.

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of management information systems*, *24*(3), 45–77.

Raubenheimer, H., & Stammen-Hegener, C. (2013). *Modern concepts of the theory of the firm: managing enterprises of the new economy.* Springer Science & Business Media.

Rudberg, M., & Cederborg, O. (2011). Aps for tactical planning in a steel processing company. *Industrial Management & Data Systems*.

Schouten, T. (2018). *Material availability planning in a low volume environment: a case study at asml (diploma thesis).* Eindhoven University of Technology.

Stadtler, H., Fleischmann, B., Grunow, M., Meyr, H., & Sürie, C. (2011). *Advanced planning in supply chains: Illustrating the concepts using an sap apo case study.* Springer Science & Business Media.

Stadtler, H., Kilger, C., & Meyr, H. (2015). *Supply chain management and advanced planning: concepts, models, software, and case studies.* Springer.

Steinrücke, M., & Jahr, M. (2012). Tactical planning in supply chain networks with customer oriented single sourcing. *The International Journal of Logistics Management*, *23*(2), 259–279.

Umble, M. M. (1992). Analyzing manufacturing problems using vat analysis. *Production and Inventory Management Journal*, *33*(2), 55.

Van Aken, J. E., & Berends, H. (2018). *Problem solving in organizations*. Cambridge university press.

van Strien, P. J. (1986). *Praktijk als wetenschap: Methodologie van het sociaal-wetenschappelijk handelen*. Assen: Van Gorcum, 1986.

Vollmann, T., Berry, W., & Whybark, D. (1988). *Manufacturing planning and control systems*. Irwin/McGraw-Hill.

Wiers, V. C., & de Kok, A. G. (2017). *Designing, selecting, implementing and using aps systems*. Springer.

A Analysis master planning symptoms at PT

In this section, the four identified symptoms at PT are described in more detail. These include nervousness, inefficient planning, high workload and unnecessary high amount of stock.

Nervousness: The first symptom identified at PT is planning instability. This can be seen in Figure 38. This figure is created at the beginning of week 1 and shows the schedule for the SMD department for weeks 1, 2 and 3 (the week numbers are adjusted due to confidential information). In week 1 it can be seen that production orders are scheduled on each SMD line. A realistic schedule is only created for week 1. This is shown with the large green and red blocks. In week 2 and 3 a collection of orders is stacked upon one another. This means that those orders are not scheduled yet. It is not possible to execute all those orders at the same time. Therefore, the planning is not feasible and unstable.

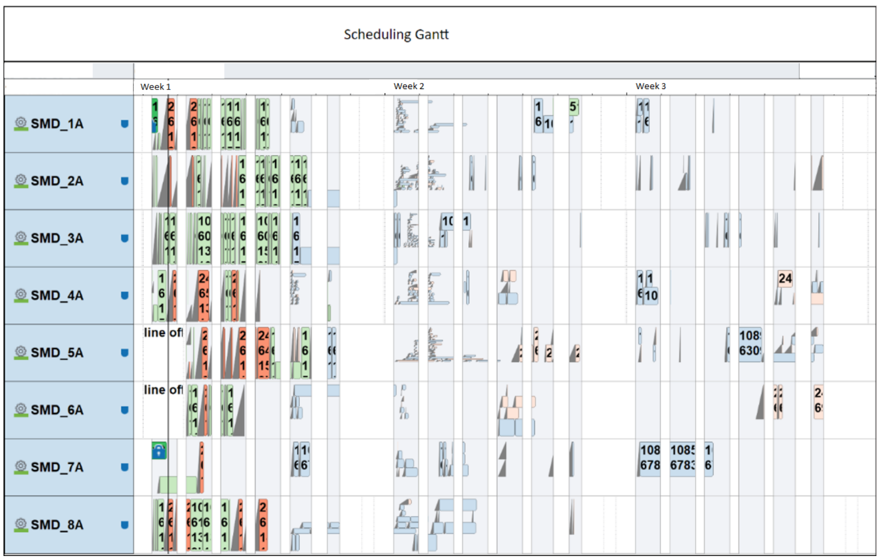


Figure 38: Scheduling Gantt chart at SMD

Figure 39 provides more insight into the unstable planning at PT. This figure shows the order status of all orders in a certain week. Blocked orders (indicated in red) are orders where at least one component cannot be delivered from (safety) stock and will arrive late. Given that the current week is 3, Figure 39 shows that there are blocked orders in previous and upcoming 21 weeks (the week numbers are adjusted due to confidential information). That means that the planning is likely to change. The number of orders (vertical axis) are not included in the figure as they are confidential.

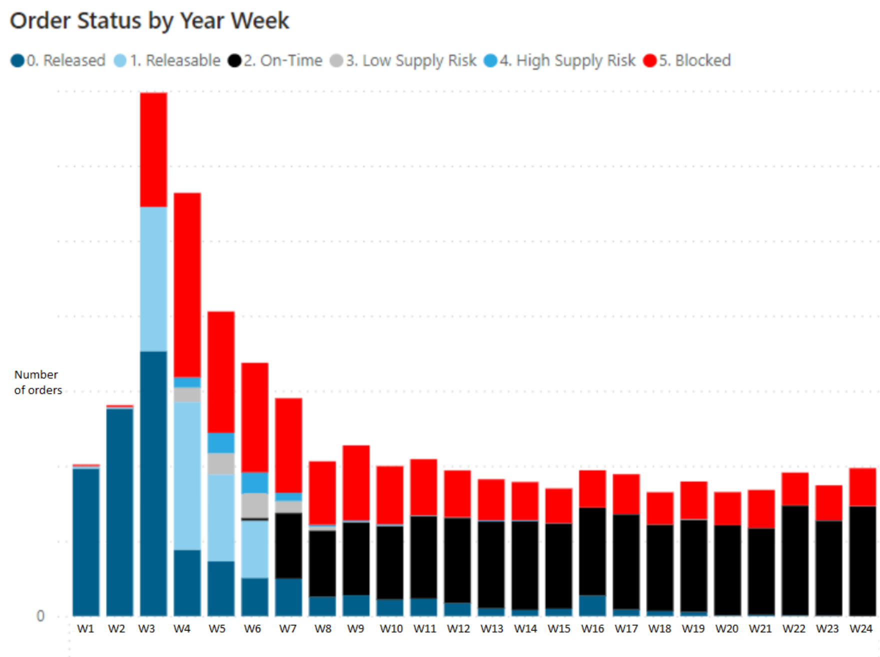


Figure 39: Order status each week

Another aspect that addresses the stability of the planning is the production order reliability. The production order reliability is measured using the RLIP. The RLIP indicates how much of the production orders are delivered on the date they were initially scheduled. In 2021 from week 1 to 51, the RLIP of the SMD department is significantly lower than the target of 80%. Therefore, it can be concluded that the planning at PT is unstable.

Planning efficiency: Inefficiencies in the planning process are the second identified symptom. It has been observed that individual planners make independent decisions regarding priorities, leading to misalignment and inefficiencies. For instance, when SA imposes requirements on both SMD and MCH, both departments should follow the same sequence. It would not be efficient to produce the MCH part when the SMD part is delayed, especially if it results in a delay of another order at the MCH department because no capacity was available.

Workload: The third identified symptom, more FTEs required to create a feasible planning, is based on the number of planners. In 2017, five planners were responsible for planning all orders. In 2022, over 40 planners are employed at PT. This increase is relatively large compared to the growth of revenue of the company in the past five years.

High stock levels: The last symptom is related to the unnecessary high amount of stock. When materials are missing in one lower BOM level, all other departments related to the same final product should also delay production. However, the other parts in the BOM are still purchased/produced, since the orders are not replanned, and the requirement date is still the same for those parts. This means that unnecessary stock is created, since a part of the product cannot be produced. Figure 40 shows the stock value and composition over time. It can be seen that there is a significant increase in stock in the year 2021 and 2022. The values are removed from the figure as they are confidential.

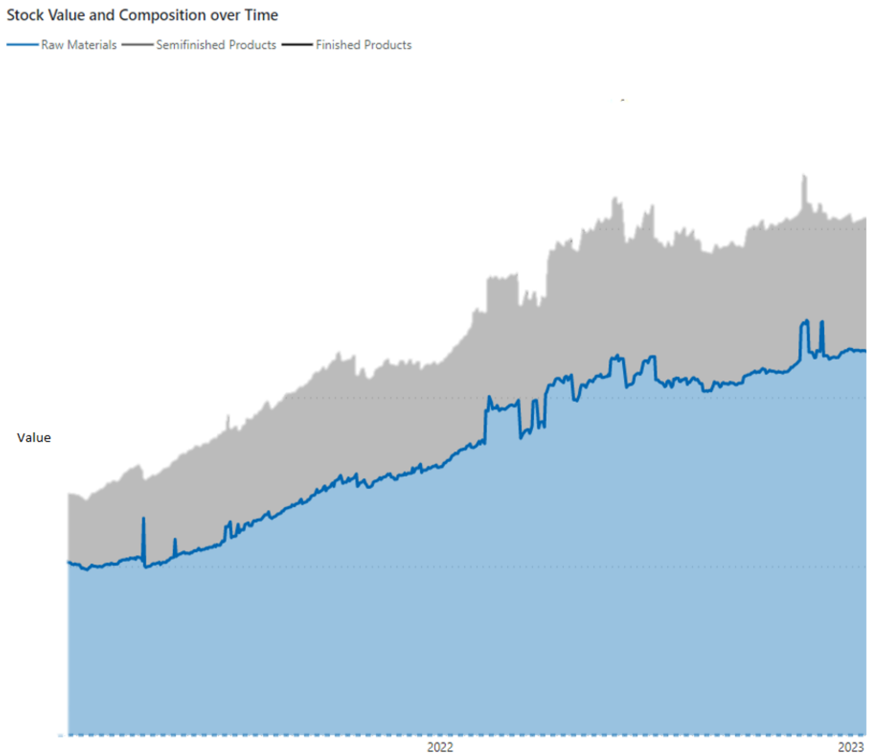


Figure 40: Stock value and composition over time

B Analysis causes master planning problems at PT

Below, three causes of the problems related to master planning at PT are analyzed in further detail. These include the focus of planners, urgency, and capacity and material reservation. MRP-I is already analyzed in detail in section 4.

Focus of planners The second category includes the causes that are part of the planning processes. The first cause is the assessment of the demand planners. This assessment is not based on the performance of PT, instead demand planners are assessed based on how well they are able to manage their client(s). Furthermore, there is no integrated overview of procurement, demand- and production planning. This means that no one oversees the full supply chain. The production planners are responsible for their department, while demand planners are responsible for the order for their client. This means that demand planners oversee the entire production process for their client only. This is illustrated in Figure 41. Here it can clearly be seen that a demand planner focuses on the departments vertically and production planners consider their own department.

	DP1	DP2	DP3	…
SMD				
CAL				
SA				
…				

Figure 41: Focus of planners

Material and capacity reservation The second cause is related to the reservation of material and capacity. Given the limited capacity and limited material availability it might already be known that it is very unlikely that an order can be made. However, if a demand planner decides to move the order to a later date, it might not be possible to move it back if the material does arrive in time since the materials are now allocated to another order. Therefore, some demand planners avoid moving the order to a later date to reserve capacity and materials. However, this results in an unrealistic and infeasible planning as shown in Figures 38 and 39.

Urgency The last element that causes an infeasible planning is the perception of the urgency of the order. When a product has several BOM layers and contains one missing part in one of the lower layers, every layer should be delayed. This does not always happen as moving the order to a later date means that the order does not seem urgent, and procurement does not actively try to obtain the missing part. This is shown in Figure 42. In this example, item 2a consists of items 3a and 3b. The supply date is later than the required date. This means that the scheduled date needs to be adjusted for all items to create a feasible planning. However, this is avoided to show the urgency of the order. That means that the planning becomes infeasible and therefore unstable as many blocked orders are still planned for upcoming week(s) as shown in Figure 39. Especially, given that one missing part in a lower layer might affect the planning in several other departments (Figure 3). The other parts in the BOM are still purchased/produced, since those parts are feasible to purchase/produce. This means that unnecessary stock is created, since a part of the product cannot be produced.

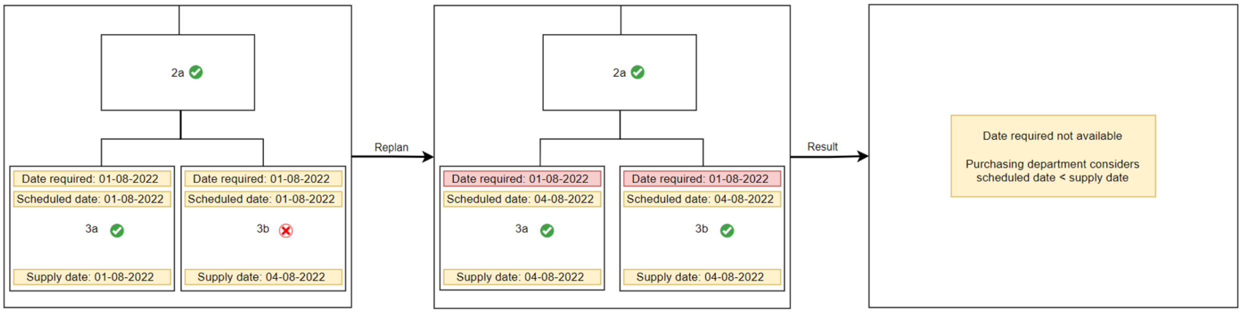


Figure 42: Urgency

C APS modules in SCP framework

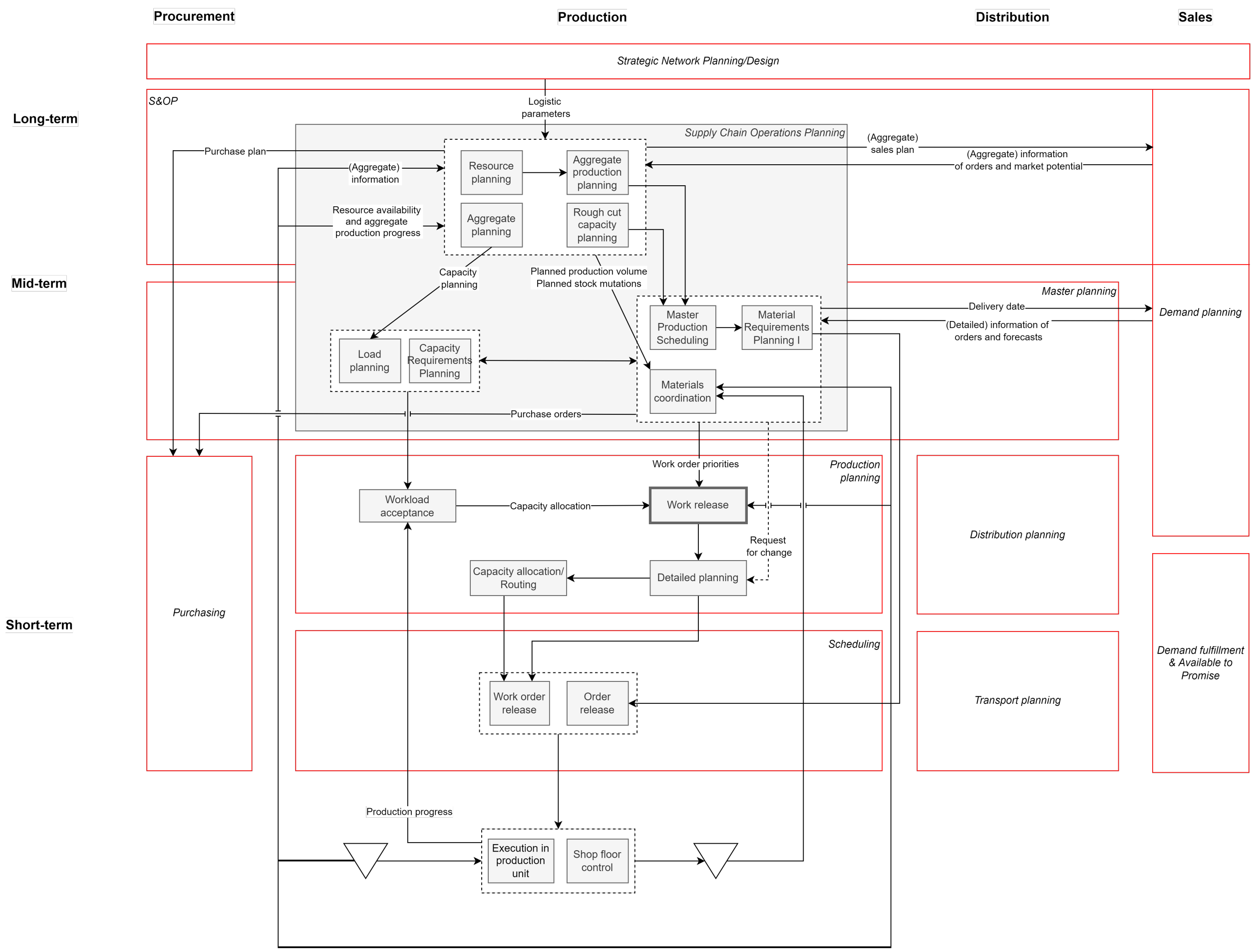


Figure 43: APS modules in integrated framework

D Production control model in integrated framework

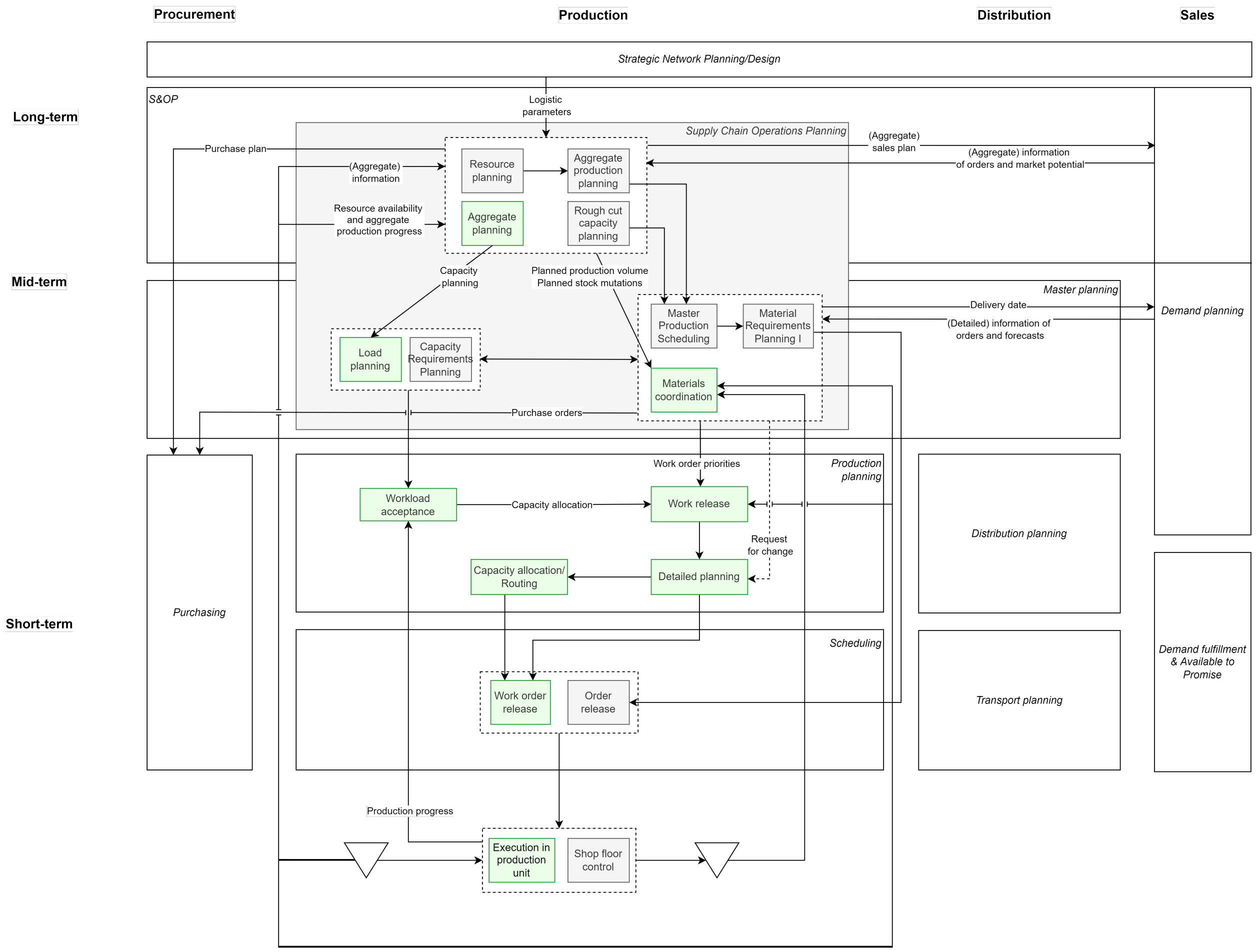


Figure 44: Production control model in integrated framework

E MRP-II in integrated framework

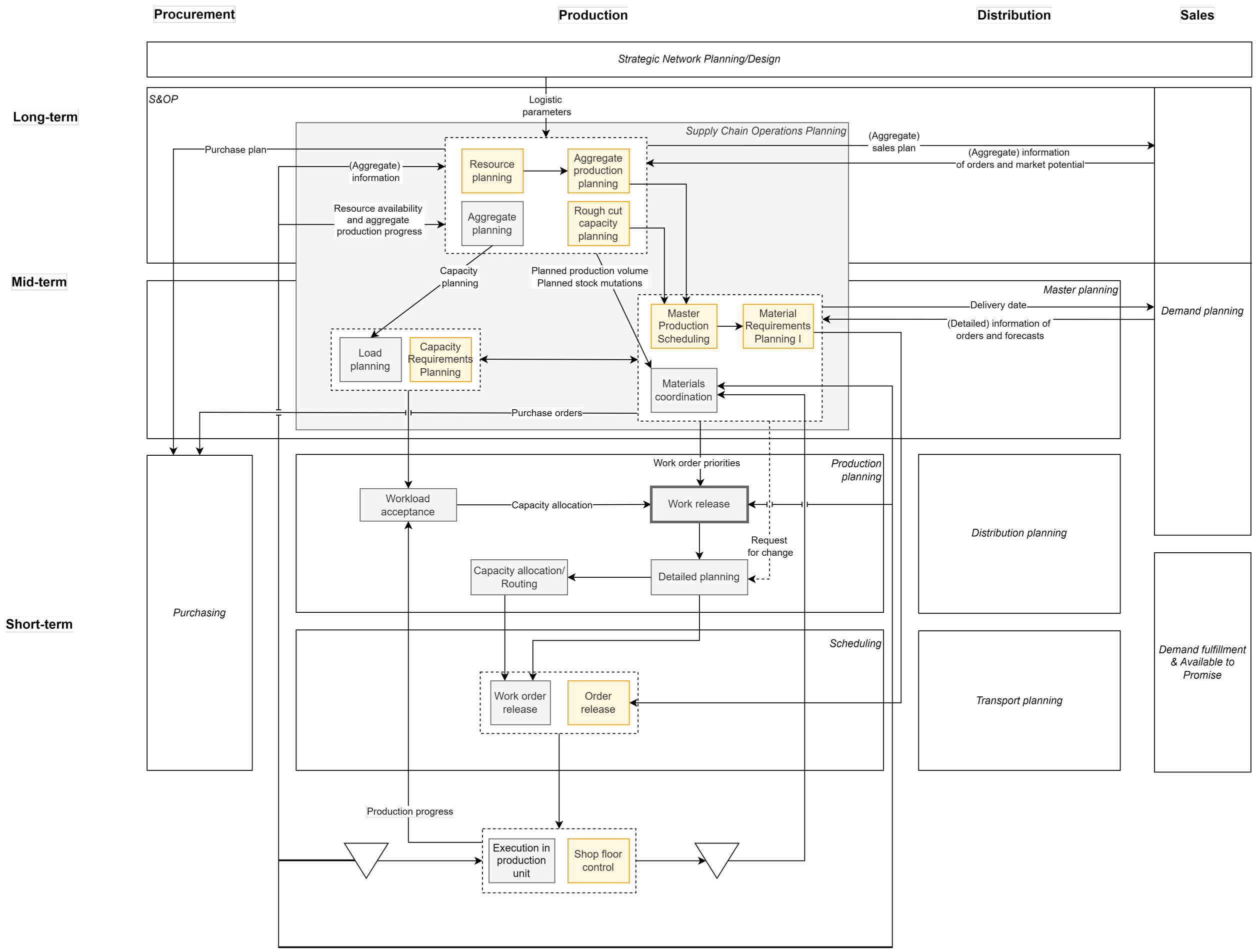


Figure 45: MRP-II framework in integrated framework

F SCOP in integrated framework

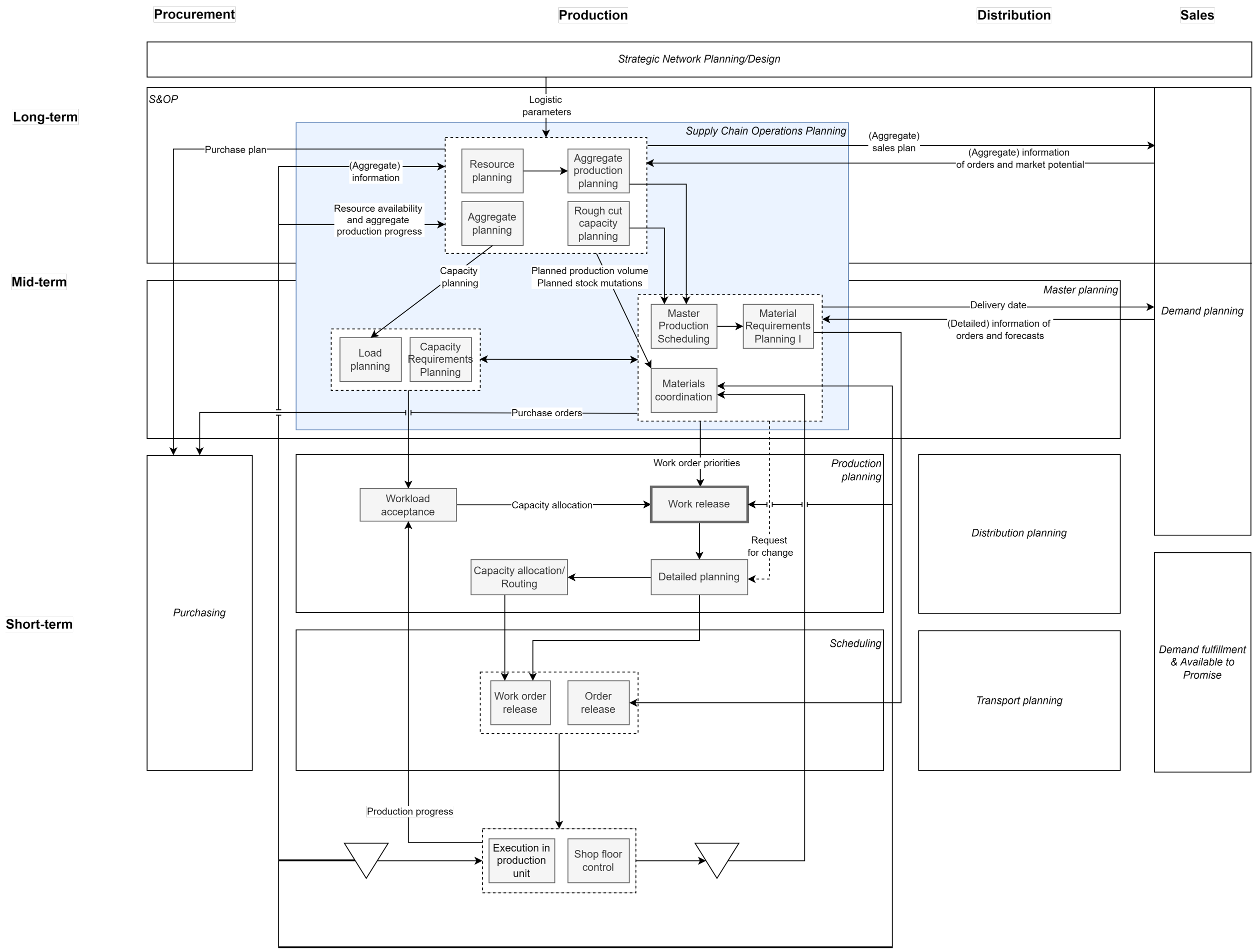


Figure 46: SCOP in integrated framework

G Data model in ArchiMate

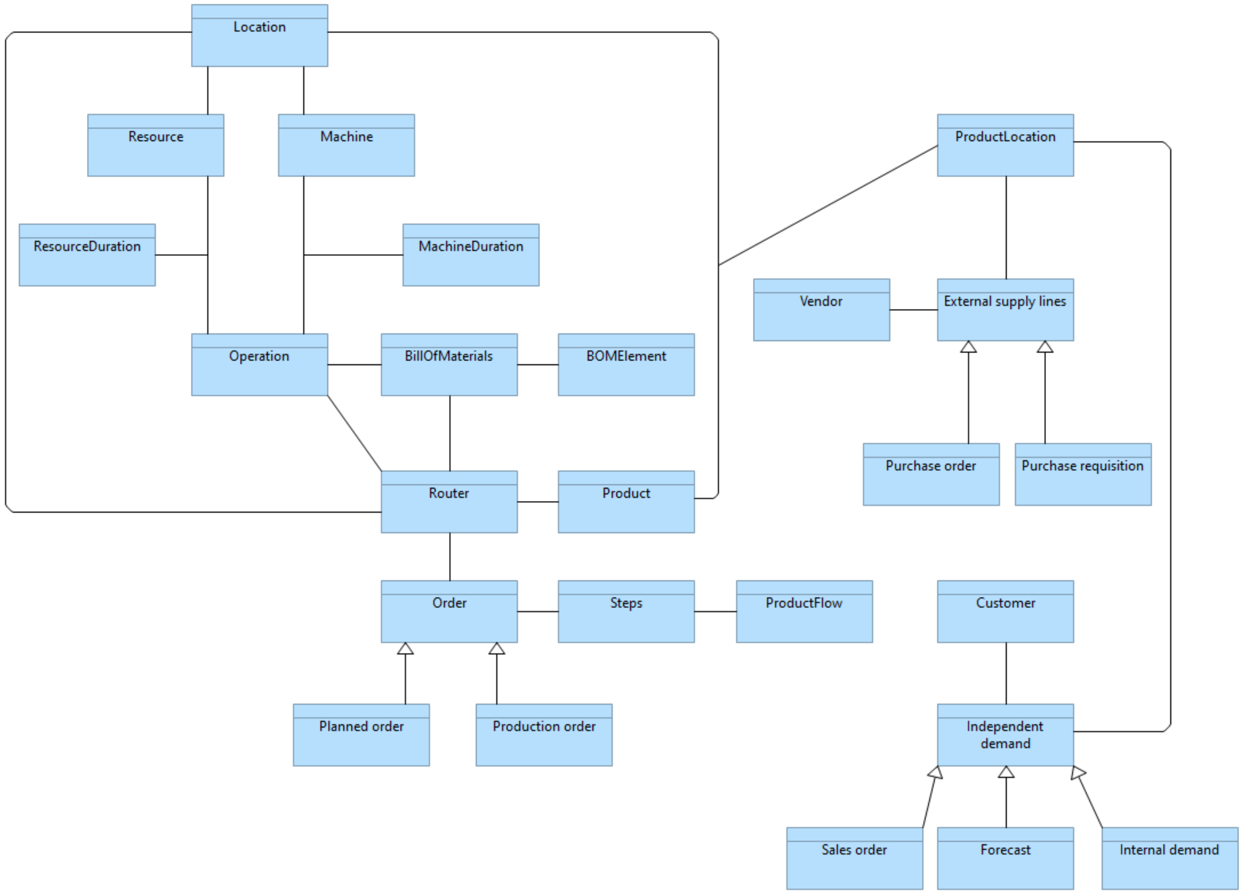


Figure 47: Data model in ArchiMate