MASTER

Capacity planning in the S&OP process
a practical model which enhances the decision-making ability of managers

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Capacity planning in the S&OP process: a practical model which enhances the decision-making ability of managers

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I. Abstract

The sales and operations planning (S&OP) process is an important process in any manufacturing environment. This process, which is on a tactical level, is typified by balancing the expected demand with the resources required for production for a specific time horizon. Whereas previously the S&OP process was conducted in isolation, a shift has been made to a more collaborative approach between departments. In doing so, the decision-making process is more streamlined which should in practice yield more overall cost-effective decisions. However, the S&OP process remains complicated as the departments have competing interests. Additionally, due to the many interdependencies between resources and production, it is difficult for the decision-maker to find an optimal production plan within the considered time horizon. This is further exacerbated by the inherent uncertainty within this process. This thesis provides a decision-support tool which helps alleviate the previously mentioned issues by providing the end-user the ability to create and assess different scenarios. The decision-support tool is developed in a structured way in which the situation under consideration is closely examined to create a conceptual model. This model was thereafter formalized by means of an MILP. The subsequent parts of this thesis provides a practical way of implementing and integrating the model such that it can be used in practice. In this process, special attention is being paid to stakeholder feedback and ensuring that the tool is end-user friendly. Additionally, a demonstration of the tool is provided which highlights how the tool can be used to extract the most value. Whilst the model provides a solid foundation for capacity related decisions in the S&OP process, further investigation is advised. The testing of the model in different environments and the potential expansion of the model are among the key topics that require further investigation. Ultimately, the proposed model could form the foundation for capacity related decision-making in a manufacturing environment.

Keywords: S&OP, capacity planning, tactical planning, resource allocation, decision-support, decision framework, uncertainty, deterministic, scenario analysis, "what-if" analysis, linear programming, ILP, MILP, supply chain management

II. Acknowledgements

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Abbreviations

BA = Business area
BoM = Bill of Material
BU = Business unit
CP = Central planner
CW = Central warehouse
DC = Distribution center
DSS = Decision support system
OEE= Overall equipment effectiveness
GL = Global logistics
GUI = Graphical user interface
HIP = Hilti integrated planning
IT = Information technology
HS = Hilti store
KPI = Key performance indicator
MIP = Mixed integer programming
MILP = Mixed integer linear programming
MO = Market organization
MPS= Master production schedule
PE = Planning engine
PT&A = Power tools and accessories
RDC = Regional distribution center
S&OP = Sales and operations planning
SKU = Stock-keeping unit
TAM = Technology acceptance model
TSC = Tool-service center

1 Introduction

The execution of this master thesis project is realised in close collaboration with Hilti. The first subsection is dedicated to providing a brief company description. Subsequently, the scope of the project is defined which provides additional details of the relevant area within Hilti for this project. After that, the motivation for this project is discussed. This is further specified and refined in the subsequent subsection which poses the central research question of this project. Based on the research question and the scope, the envisioned tangible results of this project will be presented in the subsection deliverables. This section will be concluded by an explanation of this project's structure.

1.1 Context

Hilti is a company which operates in the construction tools industry. Their products range from hand-held drills for handymen to tailor-made heavy machinery for large construction companies. Founded in 1941 by brothers Martin and Eugen Hilti in Liechtenstein, the company's main purpose was to manufacture mechanical components for various industries. The company started to expand rapidly with their first breakthrough product being the DX 100 which was the first powder-actuated tool in 1957. At this point, the only production plant which was being used was in Schaan, Liechtenstein. Due to the rapid expansion and a further diversification of product portfolio, there was a need for more production capacity. The second plant was added in 1970 which is located in Thuringen, Austria. After this, more plants followed shortly and the company started to take on a world-wide presence. Hilti now has fourteen plants in nine different countries, spanning three continents.

In order to create structure in the now complex organisation, Hilti opted to define regions. Since regions still include a broad spectrum of customers, the regions were further subdivided into Market Organizations (MOs). Within these MOs, Hilti sells either directly to their customer by shipping from central warehouses or the customer can buy from Hilti in one of Hilti's brick-and-mortar stores. The latter is the least popular as most sales are achieved through direct contact with the customers. The former method of selling to customers is preferred which is reflected in Hilti's mission. Maintaining customer relations is one of Hilti's core focus. This is also reflected in the way Hilti interacts with its customers. Instead of just being the seller of a product, they actively assist the customer with implementation and maintenance. As a result, customer retention and satisfaction is high which leads to a sustainable collaboration for both parties. Furthermore, Hilti has also specified the two Business Areas (BA) they specialize in which are electronic tools & accessories and fastening & protection. Within these business areas, one can further define product groups which are referred to as Business Units (BU). In total, Hilti recognizes eight BUs. The manufacturing of products within BUs is spread over the plants. The plants have different production lines which are used for specific stock keeping units (SKUs). This means that an SKU is only manufactured by one plant, on a specific production line, and not by other plants. Thus, a production line produces the net requirements of one (or more) specific SKU(s) based on the aggregated world-wide demand.

From the aforementioned description, it is evident that Hilti is involved in many processes within a supply chain. One can split a supply chain up into two core processes namely material management and physical distribution (Min and Zhou, 2002). In the former, materials are acquired and transformed into final products. The latter process concerns the distribution of the products to the customer. For Hilti, material management ranges from acquiring raw products to sub-assemblies to final products. Hilti manufactures all their final products in-house, except for the final products which are directly send to either a Central Warehouse (CW), Distribution Center (DC) or Regional Distribution Center (RDC). Depending on the acquired product, the manufacturing process differs. Raw materials can either be converted to sub-assemblies or used for end-products in an assembly plant. Sub-assemblies, either externally acquired or made in-house, are converted into end-products in one of the assembly plants. After the production process, the end-products are stored at one of six large warehouses otherwise referred to as HAG Warehouses. From here, the end-products are further distributed to Central Warehouses and Distribution Centers or Regional Distribution centers. After that, the products either 1) directly shipped to the customer 2) shipped to a brick-and-morter Hilti Store (HS) or 3) shipped to a Tool-Service Center (TSC). The latter is a support center where clients can bring in items for repairs and/or retrieve items which have been damaged. A simplified version of Hilti's supply chain can be found in figure 1.

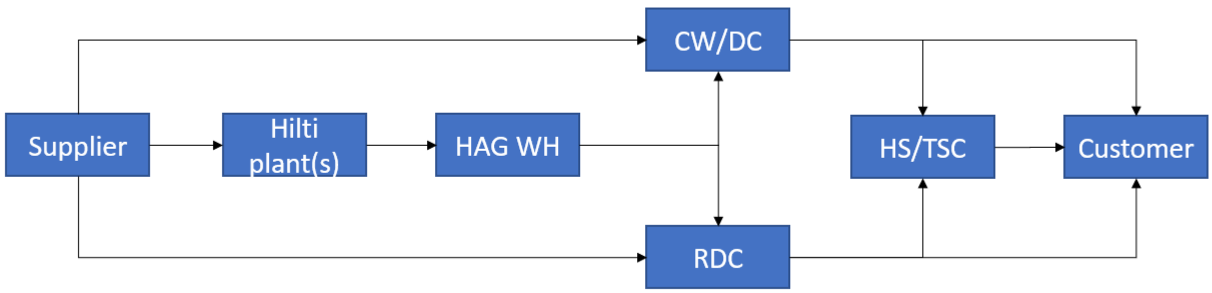


Figure 1: Simplified representation of Hilti's supply chain

1.2 Scope

This project takes place in the Global Logistics (GL) department of Hilti. This department is responsible for all operations related to supply chain management. For Hilti, this department has four main areas of operations. First, there is warehouse management. Operations within this area includes the design of the distribution network and control of warehouse processes and standards. Second, there is transport management. This area is responsible for the the transport network, selecting the appropriate mode of transport and route optimization. Third, there is materials management. Within materials management, the focus is on planning, forecasting and inventory management of all materials. Tasks include production planning and forecasting demand for all products. Finally, there is service management. This area is interlinked with the other areas as maintaining global standards is the focus for this area. For this project, the area of materials management will be considered with the other areas being out of scope. More specifically, this project will focus on the sales and operations planning (S&OP) within Hilti.

1.2.1 S&OP in Hilti

Whilst both literature and industry have various definitions for S&OP, they find common ground in the main goal of S&OP. Namely, S&OP is the means for unifying plans from both supply and demand side into one common objective which aligns both on strategic and operational level (Thomé et al., 2012). For Hilti, this does not differ. Hilti started actively investing into their S&OP process by launching a new incentive named Hilti Integrated Planning (HIP). In practice, S&OP is often used synonymously with HIP. With HIP, the goal was to create a better alignment with the different stakeholders of the S&OP process. Instead of focusing on the needs and information of one department, the departments were encouraged to share information and work with the same data. This way, there was a better overview of all relevant factors when making capacity related decisions. In order to enforce a structured process, the HIP workflow calendar was implemented. This calendar contains all deadlines on which stakeholders should perform their key monthly activities in the S&OP process. When executed accordingly, issues related to, for example, changing forecasts and/or production capacities are avoided. Due to the complexity of the S&OP process, it is important to gain an in-depth understanding about the key activities. These activities can be assigned to either the demand aspect of S&OP or the supply aspect. To reflect these categories, Hilti divided the S&OP process into two main processes namely sales planning (demand) and supply/operations planning (demand).

Sales planning

For Hilti, the S&OP process starts at the demand side. In order to gain insights into the predicted demand, they use a statistical forecast. The main input of this statistical forecast is the historic data. The statistical forecast provides a baseline upon which further adjustments can be made by the material managers in the next step. This next step is the demand review. In this step, material managers adjust the statistical forecast based upon market intelligence. The market intelligence included in this step is still on a high level. Examples are the introduction of new products and general events which results into the leading forecast. Subsequently, the leading forecast is disaggregated to Business Unit level. Additional information is gathered on product family level which further refines the leading forecast. For instance, there might be a peak in demand for certain products due to seasonality. In this case, the statistical forecast is adjusted upwards to account for the expected increase in demand. This results into the materials forecast. Finally, the materials forecast is further disaggregated on MO/Regional level. Practically, this means assigning the aggregated demand to plants within the regions. The aforementioned forecasting process is based on a period of 6-12 months. After this is done, the sales forecasts cannot be further altered. The information is fed into the Planning Engine (PE) which provides the net requirements as output. With this output, the demand aspect of the S&OP aspect is concluded. The net requirements are used as an input in the following phase which is the supply and operations planning.

Supply and operations planning

In order to translate the net requirements into a production plan, it is important to first consider the available capacity. This is the first step in the supply and operations planning and is performed by the plants. The plants provide an overview of their expected capacity for the next 18 months. Every month, the capacities are updated accordingly. The plants distinguish two types of capacity; labour hours and machine hours. The former is expressed in maximum (i.e. maximum number of shifts) and minimum (i.e. worker unions) hours. The machine hours are referred to as the technical limit which assumes that the machines are working 24 hours per week. The capacity analysis is made for every production line within the plant. With the knowledge of both expected demand and supply, the next step commences. In this next step, which is the pre-S&OP meeting, the stakeholders discuss how to balance the net requirements with the available capacity on a production line level. The stakeholders in this process are representatives of materials management on BU and global level, the production unit (plant) manager, logistics (supply) and the central planner (CP). The representatives are closely involved with the processes and thus possess the practical knowledge which is required for this meeting. The central planner guides the discussions during the pre-S&OP and S&OP and ultimately decides on the production quantities per production line for the coming month, taking into account the opinions and information of the stakeholders. It should be noted that the CP is involved during the entire S&OP process and does not just enter for the pre-S&OP and S&OP meetings. The CP is the link between all departments who are involved in the S&OP process. It is for this reason that the pre-S&OP and the S&OP meetings are lead by the CP. The CP is also responsible for providing the relevant parties in these meetings with information. In the pre-S&OP, the focus is on discussing the potential scenarios for production lines which are deemed problematic based on their status. In order to keep an overview of their production lines, the CP labels the production lines based on expected demand fulfillment. The CP can label a production line in one of three categories. If a production line can produce all the expected demand for all products produced on that line, the line status is coloured green. If the production line cannot produce the expected demand for the next 1-month period, the line status is orange. If the production line cannot produce the expected demand for more than 2 months, the line status is red. Currently, in order to save time, scenarios are only developed when a production line is labelled red or in exceptional cases. Based on the information provided by the stakeholders, the CP develops different options (i.e. produce more, produce less, etc.) per production line in the form of scenarios which are discussed in the pre-S&OP. When making scenarios, the CP considers a time period of 1 to 4 months. In the pre-S&OP, the scenarios are evaluated based on multiple criteria including service level and costs. The pre-S&OP is concluded when the stakeholders have decided on the most desirable production plan for the next month.

A couple of days after the pre-S&OP meeting, the official S&OP meeting is held. In this meeting, the CP starts by providing an overview of the current situation and the impact of decisions made in the previous S&OP based on a set of key performance indicators (KPIs). After that, the CP summarizes the relevant information (including scenarios) which were discussed in the pre-S&OP meeting. The S&OP meeting is often attended by the managers of the involved departments as well as the representatives which assisted the CP in the pre-S&OP. Unless one or more of the attendees object to the proposed production plan, the production plan which was selected in the pre-S&OP is enforced and agreed upon. After that, the S&OP plan is converted to a more detailed production plan. This is done in the master production schedule (MPS). The earlier defined monthly production plan is disaggregated to a weekly and/or daily basis. This provides the logistic planners with the required information to schedule the production. Revisiting the MPS is on a weekly basis to ensure that timely information is incorporated in the day-to-day production scheduling. Finally, the S&OP

process is concluded by distribution planning. In this stage, the CPs match realized demand with production and ship accordingly. Due to the relevancy of time in this stage, the distribution planning is also reviewed on a weekly basis.

1.2.2 Plant 4

The process described above is applicable for all of Hilti's plants. For this project, Plant 4 has been selected. Plant 4 is located in Austria, Thuringen. The plant produces for four BUs of which the BU power tools and accessories (PT&A) is the main BU. This plant can be classified as an assembly plant. In practice, this means that the production of tools is done manually. The production lines consist of multiple stations which each contain a specific part of a tool. It is set-up in such a way that a worker follows a predetermined route which visits all stations in a sequential manner. This is contrary to a tool plant, which relies on machines for production. Whilst Plant 4 is the main point of contact for this project, involvement of other plants will also be included. This is due to the fact that Hilti wants a solution that can be scaled up and therefore also be used by other plants. Therefore, whilst Plant 4 is the main focus of this project especially at the start, other plants are not outside the scope of this project.

Summarizing, this project will focus on the S&OP process within Hilti. More specifically, two processes within the supply and operations planning: capacity preview and (pre-)S&OP related decision-making. The demand related aspects of the S&OP, such as forecasting, are out of scope. The same holds for the processes which happen after the S&OP decisions have been made, such as the translation of the S&OP into the MPS. The project will be conducted in close collaboration with Plant 4. However, involvement of stakeholders in other plants will also be included as Hilti wants the result of this project to be applicable for all their plants. A visualization of the relevant area for this project is presented in figure 2.

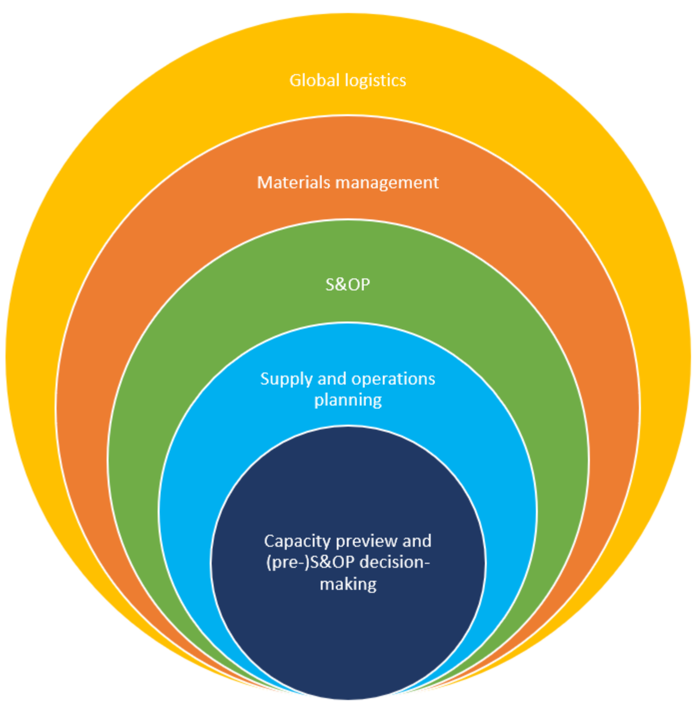


Figure 2: Relevant area for this project within Hilti

1.3 Research motivation

1.3.1 Academic

In the past, the departments involved in S&OP related discussions worked in isolation (Feng, D'Amours, and Beauregard, 2008). Consequently, the decisions made by the departments were misaligned which results into sub-optimal decision-making (Feng, D'Amours, and Beauregard, 2008;Pereira, Oliveira, and Carravilla, 2020). Instead of working on individual goals, the focus should shift to a common goal which can be, especially in the early stages, a tough barrier to break through (Grimson and Pyke, 2007). A well-aligned S&OP process can benefit an organization by synchronizing organizational plans, lower costs and improved service levels (Wagner, Ullrich, and Transchel, 2014;Ávila et al., 2019;Muzumdar and Fontanella, 2006;Bower, 2006). Whilst the research into S&OP has increased over the years, limited papers discuss practical steps to take for managers in order to successfully implement and advance their S&OP process (Thomé et al., 2012). To fill this gap, Wagner, Ullrich, and Transchel (2014) proposed an S&OP maturity model which involves 6 stages of the S&OP process with four different dimensions. The maturity model provides detailed descriptions of each dimensions and thus informs the managers how to progress in their S&OP process. One of the dimensions is Information Technology (IT). Due to the complexity of the S&OP process, IT is required for a successful S&OP process (Lapide, 2005). A more recent study by Neto, Barcellos, and Panizzon (2022) proposes a more in-depth S&OP maturity model which distinguishes multiple facets within their 6 main dimensions which they refer to as pillars. In this model, it is clear that IT plays a vital role as a derivative of IT is mentioned in almost every dimension in the higher stages of maturity. Even though literature mentions various tools which can be used for the S&OP process, limited attention is being paid to how these tools should be operated to leverage its benefits. Furthermore, the tools are often mentioned on a departmental level. For instance, for the forecasting process one can use moving average. As stated before, S&OP is a joint effort and the tools used in the process should be tailored to achieve a common goal. Further light should be shed on how the tools can and should be used in practice to maximize the benefits of the overall S&OP process.

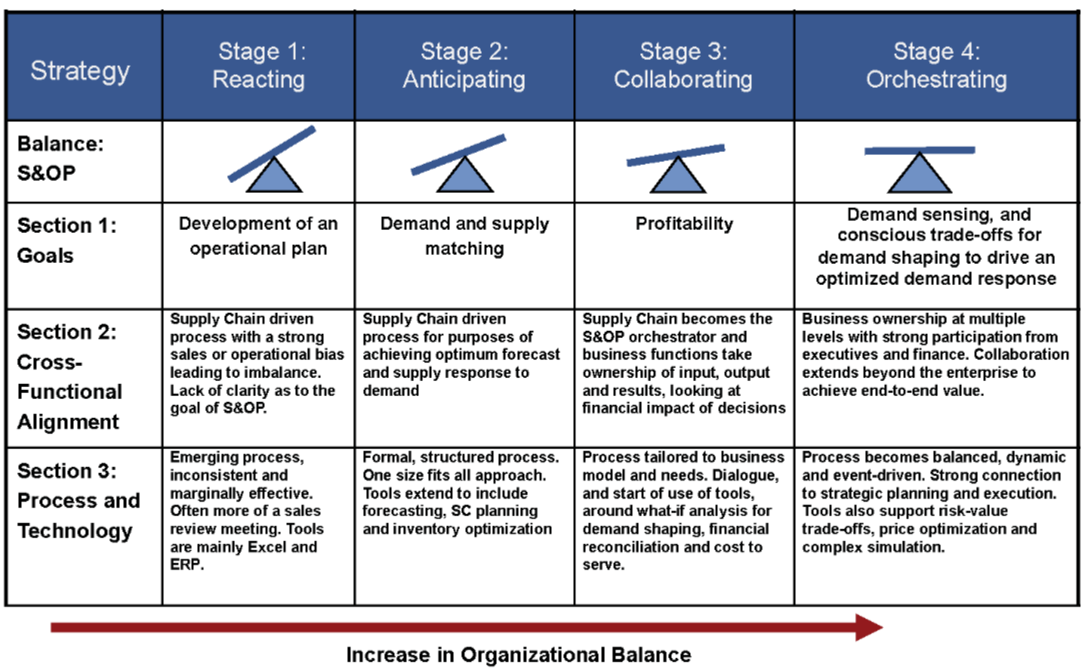
1.3.2 Practical

From Hilti's perspective, this thesis continues on an ongoing project which started in 2019. At this point in time, Hilti was looking to further develop themselves in the S&OP process by creating a mathematical model which provides the cost-optimal scenario. The results of this research can be found in the thesis by Vargas de Kruif (2020). This project was a success but due to the complexity of the problem, one crucial parameter which was identified in the paper could not be incorporated into the model. This parameter was material availability. For this reason, research continued with another thesis by Wagemakers (2022) into this subject. The main objective of this thesis was to provide a better visualization of the material requirements of each product. This was done by performing a close inspection of every Bill of Material (BoM). The result of that thesis lead to a dashboard which provides the CP with an overview of material availability. Even though both of the theses were a success, the project is not yet finished as one crucial element is missing. In order to finish the project, Hilti wants a decision-support tool for their CPs which incorporates and operationalizes the knowledge gathered by both aforementioned theses' work in a user-friendly way.

As mentioned in the previous subsection, the CP plays a crucial role in the S&OP process. Due to their central role, the CP requires access to timely and accurate data in order to make their decision. Currently, there is a significant amount of manual labour involved to both retrieve the data and develop scenarios accordingly. As a result, creating scenarios is a time-consuming endeavor. Whilst scenario templates are currently being offered to the CPs, the actual use of this template is still limited. One of the reasons is that the current template does not sufficiently encompass the currently common scenarios, let alone the uncommon scenarios. Consequently, the CP has to gather the data and perform the calculations manually which is a time-expensive effort. This further calls for a tool which proactively supports the CP by displaying the correct information and reducing the manual effort exerted by the CP.

Additionally, the main challenge of S&OP should be emphasized namely balancing supply and demand. Even with the aforementioned information available, the CP still needs to make a decision. Ultimately, this decision should be made to accomplish a goal such as maximize service level or minimize costs. Often times, these goals cannot be accomplished simultaneously. For example, to improve service level one might increase the stock of the end products to safeguard against a potential increase in demand. In turn, the inventory cost also increase. Irrespective of the goal set by the CP, the impact of each decision on various KPI's should be explicitly known to the CP. Currently, there is still a significant amount of ambiguity regarding this topic which can be solved by accurately displaying what the consequences are of a decision by using a decision-support tool.

At the core of Hilti's motivation is development. Hilti recognizes the rise in importance of quick decision-making which is relevant for all their processes, S&OP included. To assess their growth in terms of S&OP, Hilti uses an enhanced version of the Gartner S&OP maturity model. For illustration, a depiction of the original model created by Gartner can be found in figure 3 (Barrett and Uskert, 2010). The enhanced version Hilti uses is more detailed and is more accurately aligned with the operations and vision of Hilti. Hilti's aim is to progress from an S&OP process that is currently classified in the enhanced Gartner model as in between standard and advanced to an advanced S&OP process.



Strategy	Stage 1: Reacting	Stage 2: Anticipating	Stage 3: Collaborating	Stage 4: Orchestrating
Balance: S&OP				
Section 1: Goals	Development of an operational plan	Demand and supply matching	Profitability	Demand sensing, and conscious trade-offs for demand shaping to drive an optimized demand response
Section 2: Cross-Functional Alignment	Supply Chain driven process with a strong sales or operational bias leading to imbalance. Lack of clarity as to the goal of S&OP.	Supply Chain driven process for purposes of achieving optimum forecast and supply response to demand	Supply Chain becomes the S&OP orchestrator and business functions take ownership of input, output and results, looking at financial impact of decisions	Business ownership at multiple levels with strong participation from executives and finance. Collaboration extends beyond the enterprise to achieve end-to-end value.
Section 3: Process and Technology	Emerging process, inconsistent and marginally effective. Often more of a sales review meeting. Tools are mainly Excel and ERP.	Formal, structured process. One size fits all approach. Tools extend to include forecasting, SC planning and inventory optimization	Process tailored to business model and needs. Dialogue, and start of use of tools, around what-if analysis for demand shaping, financial reconciliation and cost to serve.	Process becomes balanced, dynamic and event-driven. Strong connection to strategic planning and execution. Tools also support risk-value trade-offs, price optimization and complex simulation.

Figure 3: Original version of the Gartner S&OP maturity model

1.4 Research question

Based on the previous subsection, one can find both academic and practical evidence of the problem encountered by Hilti. It is furthermore noted by the company that, in order to enhance the S&OP decision-making process, scenario analysis should be incorporated in a solution. The aim for this thesis is to contribute to this topic. This will be done by answering the following central research question:

Research question: How can scenario analysis be incorporated and operationalized into a decision-support tool which supports the central planner in making capacity related decisions in the S&OP process?

Due to the fact that the central research question provides a broad description of the topic of this thesis, it is decided to include subquestions. The subquestions aim to provide more direction for the research by focusing on the relevant aspects of the central research question. In the end, combining the answers to the subquestions provides a comprehensive answer to the central research question. First, it is important to perform an in-depth analysis in the current decision-making process. In doing so, it should become clear which parameters are prevalent in making decisions. This process will be supported by closely collaborating with the CPs. Therefore, the first subquestion is:

Sub question 1: What parameters are key in making decisions in the current process?

Additionally, it is important to know how a CP is supported in their decision-making process. More specifically, it is important to investigate which tools the CP has access to which benefits their decision-making process. The second subquestion is:

Sub question 2: What tools are currently being used to aid the central planner in making decisions?

The previous two subquestions provide a detailed description of the current decision-making process of a CP. This combined with the knowledge gained from the literature review provides a foundation for identifying opportunities for improvement. Thus, the following sub question is posed:

Sub question 3: What are the most common challenges currently faced by the CPs during the decision-making process?

In developing the new decision-support tool, it is important to consider the interaction between the decision-making tool and the CP. The tool should serve as an instrument to assist the CP. It could do so by providing a numerical or graphical output. Furthermore, the amount of control the CP has over the output of the tool is important to consider. It is therefore important to determine how the tool should be developed in order to make it suitable for interaction with the CP. Thus:

Sub question 4: How can the tool be developed to ensure user-friendly interaction?

Finally, after the tool has been developed and implemented, it is important to measure its performance. Performance in this context is difficult to measure as there are multiple factors which can be assessed. It is therefore important to develop and/or establish KPIs accordingly which can be measured quantitatively. Furthermore, these KPIs should be compared to a baseline performance. Establishing this baseline is essential since this can be used as a benchmark to compare the result of a decision made with the tool with a decision made without the tool. The final subquestion is therefore:

Sub question 5: How can the performance of the decision-support tool be measured?

1.5 Deliverables

In this subsection, the envisioned tangible results of this research are outlined. As with any research, research should provide mutual benefits for academics as well as the non-academic partners (D'este and Perkmann, 2011). The value added for the academic side will be discussed in section 3 of the report. This subsection focuses on the non-academic side. Based on the scope of this project and the main research question, the following deliverables were defined. First, a decision-support model will be created using the knowledge gained by the literature review and the information provided by the CPs. After the model is established and conceptually validated, the model will be integrated in an application which can be used by the company. The next step is to verify and operationally validate the model by using dummy data. After that, the application is transformed into an actual tool which can be interacted with by the CPs. At this point, CPs can adjust parameters based on the scenarios they want to explore which ultimately results in numerical and/or graphical output. Based on this description, one can see that there are three key stages in the project which are all defined as deliverables. A concise overview of these deliverables can be found in the list below.

- A decision support model for capacity planning which can be scaled-up to different plants.
- Integration of the decision model into an application for scenario planning to support the decision-maker (central planner).
- Operationalize the decision support application (system) for cost-optimal scenario analysis for supply chain planning into the capacity preview phase of the S&OP process.

1.6 Project outline

To conclude this section, a brief description will be provided on the structure of this report. The previous subsection already highlights the overall direction of this project. This subsection provides more substance by detailing the steps necessary to realize the desired results. The first step in this process is to develop a methodology. This methodology will provide a theoretical foundation which will be used to fit and structure this research. In order to obtain a better understanding of S&OP, specifically related to capacity related decision-making, a literature review will be performed. The goal of the literature review is two-fold. First, it is used as an informative means by providing an overview of the current S&OP practices. Second, it can provide valuable information regarding best practices and therefore be used to derive solutions for the context at hand. In parallel to the literature review, multiple interviews will be held with the eventual end-user of the decision-support tool which are the CPs. The goal of the interviews are to gather more information about how the CPs envision the decision-support tool and what data is required to make it effective. Based on the information provided by the CPs and the literature review, a conceptual model will be build. In this phase, close collaboration with the CPs is essential since their input is required to shape an appropriate model. When an appropriate conceptual model is formulated, the model will be formalized by transforming it into a mathematical model. After that, a suitable environment will be selected to program this mathematical model in. When the program is properly validated and verified, the model is going to be converted into an application. When the application is considered to be suitable for use, it will be operationalized and made available to all CPs. After that, the operationalized model will be tested in practice by using case studies. In doing so, a hypothetical production line is created to run these case studies. After that, the scalability of the model will be discussed and aa practical implementation plan is presented. Finally, the report will be concluded by revisiting the research question, highlighting the limitations of this research and providing suggestions for future research.

2 Methodology

In this section the methodology used for conducting the research for this project will be explained. The methodology provides a rough guideline on which steps are taken to obtain a desirable end result. For this project, the methodology is based on the problem-solving cycle as defined by Van Aken, Berends, and Van der Bij (2012). This cycle consists of five core steps. Since the authors depict the methodology as a cycle, there is no start or end point. However, for any project it is first important to investigate the problem at hand which is done in the problem definition step. In this step, the problem as indicated by the company is investigated and scoped such that it fits within the project. After that, the problem can be analyzed and a diagnosis can be made. Subsequently, a solution design can be made which fits the context at hand and tackles the problem at its core. The solution is theoretically sound and appropriated to ensure practical relevance and functionality. After that, the intervention can take place. The realization of this step, alongside the evaluation and learning steps are outside the scope of this project. This is due to the fact that these steps are up to the company to perform. However, this project will aid the company in these steps by providing an implementation guideline as well as future directions which assist the company in achieving the most value out of the project. Within this cycle, the problem mess is at its core which influences every step in the cycle. A visual representation of this cycle is depicted in figure 4.

Problem definition

In the first step of the cycle the problem was defined and scoped. For this project, the current problems and challenges Hilti faces have been highlighted in section 1.3. These have been derived from the initial project description and further refined by meetings with the company representatives. Summing up, there is a lack of quantitative support when making capacity related decisions for the CP which ultimately leads to inefficient and sub-optimal decision-making.

Analysis and diagnosis

The second step was to analyse the problem and gather information about the root cause of the problem. This was done by arranging one-on-one meetings with the stakeholders involved. Furthermore, S&OP meetings were attended to observe the problem from an outside perspective. Additional information was gathered from previous projects and presentations which provides an objective overview of Hilti's S&OP process. The analysis revealed that the problem as defined previously is representative of the problem as experienced in practice. The main issues causing the problem are 1) lack of time due to short-decision time-frame, 2) difficulty obtaining required data and 3) high complexity in decision-making.

Solution design

In the third step, a fitting solution design will be developed that fits the current context. To gain inspiration for the solution design, an extensive literature review will be conducted. In the environment of capacity planning, uncertainty plays a key role which is reflected in the literature. Generally, there can be two types of model which fit the context namely stochastic and deterministic models. Due to the context, stochastic models which inherently includes uncertainty are deemed unsuitable due to the unavailability of historic data. Additionally, the model should be able to provide a unique optimal solution for each scenario under consideration and therefore a deterministic model is selected. To ensure that uncertainty is still included in this model, the deterministic model will be adjusted accordingly in the form of allowing the end-user to manually adjust the parameter values. In this process, it is also important to regularly schedule meetings with the stakeholders. The main purpose of these meetings will be to keep the stakeholders apprised of the model's development and also gather context-specific constraints and demands. Additionally, it is important to determine whether the stakeholders prefer practicality or accuracy as this shapes the direction of the model development.

After an initial model is developed, an appropriate environment should be selected for integration. This environment should both be 1) able to execute the model and 2) be user-friendly. For this step, it is beneficial to first focus on the execution of the model. When the model's output is verified and validated, steps can be taken to ensure user-friendliness if that is required. After these steps are taken, the model can be tested by the CPs. This can serve as a final round of feedback to ensure that all elements which are relevant for the CP are accounted for. The solution design phase can be concluded when the final model is verified and validated by the CPs and the model adheres to the requirements as described in section 1.5.

Intervention

The intervention step is often executed by the company itself when the project has ended. However, to aid in this process, the final model is validated in the previous step to ensure that the model is an appropriate fit in practice. Additionally, the model will be tested for its scalability and an implementation plan will be provided for the company such that the actual intervention itself, which is performed by the company, can be adequately executed.

Evaluation and learning

In the final step of the cycle, the company has employed the model in practice and evaluates its output. At this point, the project has already concluded. However, the report provides future directions for the company, including potential process adjustments which can be later considered by the company in this stage.

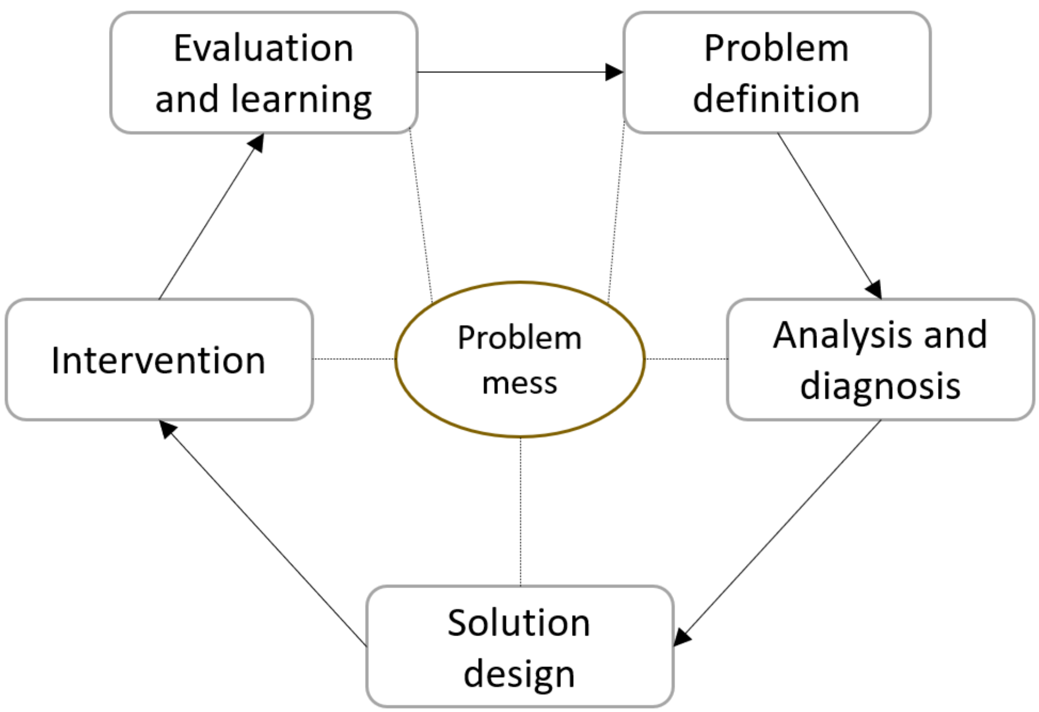


Figure 4: The problem-solving cycle as described by van Aken, Berends & van der Bij (2012)

3 Literature review

In this section, an in-depth literature review will be performed. The first subsection will be dedicated to developing a better understanding of S&OP decision-making by comparing Hilti's S&OP decision-making process to literature based on four aspects. The second subsection will highlight the interaction between systems, algorithms and the human end-user. Due to the fact that the main deliverable of this project is a decision-support system (DSS), it is first important to define what a DSS is and its potential benefits. After that, it is important to understand the human factor. After all, the central planner has to work with the decision support system. It is therefore important to investigate this interaction and how the algorithm embedded in the system can be leveraged for optimal results. This subsection will also provide a brief overview of specifically the use of scenario analyses in DSS, also in relation to S&OP. This section will be concluded by a brief summary which aims to visualize the place of this thesis with respect to the current S&OP literature.

3.1 S&OP decision-making

For S&OP decision-making, it is important to investigate the aspects which are relevant to this topic. In the first section, a description was provided on the current S&OP decision-making method of Hilti. This subsection aims to highlight the differences between Hilti's S&OP decision-making process and the S&OP decision-making process as described by literature. Based on the description of Hilti's S&OP decision-making process, several aspects could be identified. These are the planning horizon, the S&OP representatives and decision-maker, S&OP considerations and S&OP performance management. The remainder of this section will be dedicated to provide more insights on each of these aspects. A brief summary of the differences on these aspects between Hilti and literature is provided in table 1

3.1.1 S&OP planning horizon

In order to gain a better understanding of S&OP decision-making, it is first relevant to recognize its place in the three different planning levels as defined by Stadtler et al. (2015). On the highest level, there are strategic decisions. These decisions have a structural impact on the supply chain. Therefore, strategic decisions are often made for a time horizon of several years. Mid-term planning, also referred to as, tactical planning, includes decisions made for a time horizon of six to 24 months. At this level, decisions are made regarding rough quantities and resource usage within the structured supply chain. Finally, on the most detailed level, these numbers are further defined to ensure an accurate coordination of all activities. This level is also referred to as the operational level. The planning horizon for these types of decisions are a few days to three months. Based on this description, one can see that whether a decision falls in the category strategic, tactical or operational solely depends on the time horizon. The importance of this classification should not be underestimated as authors can use different attributes to classify a decision as, for instance, a strategic one (Khalifa, 2021). Even within the same classification, different time horizons can be linked to the three different levels. For instance, Pereira, Oliveira, and Carravilla (2020) state that tactical decisions are decision made with a planning horizon of a few months to one year.

The general consensus within literature is that the decisions related to the S&OP process are of a tactical nature (Feng, D'Amours, and Beauregard, 2008;Thomé et al., 2012;Pedroso, Silva, and Tate, 2016). This is supported by Thomé et al. (2012) & Affonso, Marcotte, and Grabot (2008) who state that the planning horizon for S&OP decisions are 3-18 months and 12-18 months, respectively. It also supports the description of Stadtler et al. (2015), as S&OP discussions are about rough quantities on an item family level. These discussions, and the further decisions made regarding S&OP, should take place at least once per month (Noroozi and Wikner, 2017;Feng, D'Amours, and Beauregard, 2008;Boyer Jr, 2009).

3.1.2 S&OP representatives and the decision-maker

To provide more context to the S&OP process, it is important to identify the departments which are and/or should be involved in the process. Kreuter et al. (2021) mentions that there are three "classical" departments involved namely sales, marketing and production. Based on the description, the authors seem to suggest that these departments are central to the process and thus should always be involved. Literature regarding the departments involved is however ambiguous. For instance, Pedroso, Silva, and Tate (2016) add the departments product development, supply and finance to the departments which are involved in the S&OP process but omit production. The presence of the finance department in the S&OP process is further supported by several authors (Noroozi and Wikner, 2017;Ivert and Jonsson, 2010;Dunn, 2019;Stahl and Wallace, 2012. Further examples include the presence of the supply chain department (Stahl and Wallace, 2012;Dunn, 2019) and procurement (Feng, D'Amours, and Beauregard, 2008;Ivert and Jonsson, 2010). Even though there are different departments involved according to different authors, one can argue that the different authors use the function each department fulfills in the process synonymously. It is however difficult to verify this hypothesis as the authors usually mention the departments involved but not the specific role of the department within the S&OP process. The involvement of more departments in the S&OP process contributes to one of S&OP's most important purpose which is better interorganizational alignment (Wagner, Ullrich, and Transchel, 2014). Although this is beneficial, one should note that the decision-making process will become more complex as more departments enter the S&OP discussion. Additionally to the aforementioned departments, authors also mention the presence of a so-called "S&OP champion" (Grimson and Pyke, 2007;Macon, 2020). The authors argue that this person increases the effectiveness of S&OP but do not specify how such a person practically adds value to the S&OP process.

Similar to the departments involved in the S&OP process, literature does not present one agreed-upon person who ultimately makes the executive decision in the S&OP process. This executive decision should be interpreted as the production plan for the coming month(s). Furthermore, literature does not distinguish between the potential different representatives of each department for the pre-S&OP and S&OP meeting. The overall consensus is that the pre-S&OP meetings (when mentioned) and the S&OP meetings are led and attended by senior management (Feng, D'Amours, and Beauregard, 2008;Tinker, 2010). According to Sheldon (2006) the executive decision should be made by the CEO. Other authors provide a more vague description such as a top management leader (Boyer Jr, 2009) or a senior executive leader (Dunn, 2019). Based on these description one can derive that ultimately, the final executive decision for an S&OP meeting according to literature, should be made by a representative of management (Noroozi and Wikner, 2017).

3.1.3 S&OP considerations

Whilst alignment within the organization is one of the primary drivers for an S&OP process, another reason to invest in an effective S&OP process is to better balance supply and demand (Thomé et al., 2012;Lapide, 2011;Dreyer et al., 2018). To make these decisions, a variety of parameters and/or variables should be considered. In doing so, one can either modify variables and/or parameters related to the expected demand or modify variables and/or parameters related to the supply (Olhager, Rudberg, and Wikner, 2001). To deduce the parameters and variables which are being considered, it is important to look at the models developed which construct the optimal production plan. These models can be either classified as mathematical models or heuristics. For instance, Wang, Hsieh, and Hsu, 2012 showcase a Mixed Integer Programming (MIP) model. However, the authors opt to use a heuristic instead as the MIP formulation is too complex to solve in a timely manner. They found that, on average, the heuristic performs 6% worse than the solution obtained from the MIP. Literature regarding the use of mathematical models in this context is plentiful. Generally speaking, the variables and parameters identified in these articles are classified as sales, production, distribution and procurement, (see for example Nemati, Madhoshi, and Ghadikolaei (2017) and Feng, D'Amours, and Beauregard (2008)).

Whilst there are variables which are present in all models, such as inventory costs, the models are often developed for the context at hand. This is further corroborated by Pereira, Oliveira, and Carravilla (2020) who performed a literature review on the current decision-making models used in S&OP. In their paper, the authors present an exhaustive list of variables and parameters they encountered during their literature review. The authors note that there is a considerable amount of diversity in the modelling approach of such models which is often due to the fact that they are developed for a specific context. Therefore, additional research should be performed to develop a generic but dynamic model which can be used in different contexts (Pereira, Oliveira, and Carravilla, 2020).

It is also important to look at the objective function of the mathematical models as the objective function specifies the value which will be maximized/minimized. For almost all the models, either the profit (or value) is maximized (Feng, D'Amours, and Beauregard, 2008;Nemati, Madhoshi, and Ghadikolaei, 2017;Marier et al., 2014) or the costs are minimized (Taşkın et al., 2015;Vargas de Kruif, 2020;Wang, Hsieh, and Hsu, 2012). One exception is model developed by Sodhi and Tang (2011) as this model aims to minimize weighted risks associated with demand uncertainty. Interestingly, although improved service levels are often mentioned as a benefit of an effective S&OP model (Wagner, Ullrich, and Transchel, 2014;Bower, 2006), the incorporation of service level into an objective function has received limited attention.

3.1.4 Measuring S&OP performance

To conclude this subsection, it is important to investigate how one measures the impact of the decisions being made in the S&OP process. After all, KPIs are paramount as they can serve as a baseline and help identify opportunities for improvement (Tinker, 2010). S&OP performance in this context is the performance resulting from the decisions being made related to the production quantities. It is important to make this distinction as there is plenty of literature discussing the effects of S&OP on firm performance which is highlighted by the systematic literature review performed by Thomé et al. (2012). An important finding by the authors is that firm performance is an ambiguous term in the literature as authors do not measure this construct the same way. Further research extends on this by adding that it is important to standardize the way performance is measured (Hulthén, Naslund, and Norrman, 2016).

Due to the impact of S&OP on multiple departments and facets, KPIs should be selected accordingly. One way to do this, is to develop an scorecard (Milliken, 2008). The authors define multiple KPIs per department but also state that the proposed scorecard is an example. Therefore, the provided scorecard might be of better use as a baseline or indication of how performance can be measured as it might not include all relevant KPIs. A more exhaustive list of KPIs which are being used in practice are provided by Hulthén, Näslund, and Norrman (2016). The authors distinguish between measures which can be used for both demand and supply side. However, KPIs which consider both the demand and supply side simultaneously are not identified. Due to the diverse and often conflicting interest of the departments involved in the S&OP process, there might be a call to develop such construct.

Similar to the decision-making models used, the KPIs used to measure performance are also often context-specific. For decision-making models, this finding led to the conclusion that there is a need for more generic models (Pereira, Oliveira, and Carravilla, 2020). For KPIs however, the opposite is argued as performance indicators should be selected which are appropriate for the context at hand (Hulthén, Näslund, and Norrman, 2016).

S&OP aspect	Hilti	Literature
Type of decision	Tactical	Tactical
Time horizon decision	1-4 months	3-18 months
Frequency	Once per month	At least once per month
Representatives	Materials management, production, logistics and the central planner	Combination of sales, marketing, production, product development, supply, finance, supply chain
Leads the S&OP meeting	Central planner	Senior management
Decision-maker	Central planner	Member of management
Decision criteria	Machine hours, labour hours, material availability and timely contextual factors	Variables related to sales, production, distribution, procurement and context-specific factors
Decision objective	Context-specific, minimize cost when possible	Minimize costs or maximize profit
Performance management	Monthly review where actual production vs planned production is the main metric	Scorecard, context-specific

Table 1: Overview of relevant S&OP characteristics and the general approach by literature and Hilti.

3.2 Systems, algorithms and human decision-making

With the rise of the use of algorithms used in decision-support systems, it is important to investigate the general attitude of the human factor towards such systems (Hou and Jung, 2021). In order to do so, it is first important to define what a decision-support system is. According to Shim et al. (2002), decision-support systems (DSS) are "computer technology solution that can be used to support complex decision making and problem solving". Based on this description, one can consider a DSS a form of information technology (IT) as IT concerns a broad range of technologies which are related to the information processing capabilities of a firm both on hardware and software level, including applications used by the firm (Onn and Sorooshian, 2013). Within the S&OP literature, the presence and importance of IT cannot be missed. For instance, IT is one of the key dimensions in S&OP maturity models (Grimson and Pyke, 2007;Wagner, Ullrich, and Transchel, 2014). This is further supported by Tinker (2010) who state that IT is a basic requirement in the S&OP process. Therefore, the implementation of a DSS for the S&OP process can be considered a beneficial endeavor as it showcases maturity in the process. Moreover, Bharadwaj (2018) argues that a DSS is essential for the S&OP process. Thus, the importance and prevalence of DSS in S&OP should not be underestimated.

In general the use and benefits of a DSS are widely discussed, as the purpose of a DSS is to support the decision-makers in making better decisions by extending one's cognitive ability (Todd and Benbasat, 1999). A DSS can either support by making decisions more efficient (i.e. less time and effort exerted) or more effective (i.e. higher quantifiable performance) (Evans and Riha, 1989). The latter is however disputed by Todd and Benbasat (1992) who found whilst the effort exerted was significantly lower with a DSS, the decision quality in terms of performance was the same for users with and without a DSS. However, other research suggest that performance does in fact increase when DSS are used (Sharda, Barr, McDonnell, et al., 1988;Van Bruggen, Smidts, and Wierenga, 1998). It is therefore paramount that end-users actually use the DSS. As stated before, a DSS is a form of IT and the determinants of how people adopt new IT can be explained by the Technology Acceptance Model (TAM) developed by Davis (1986). This model, which has received widespread attention in literature for almost every domain, states that technology acceptance is determined by two variables namely perceived usefulness and perceived ease of use. In their subsequent research they found that, whilst both significant, the relationship between perceived usefulness and technology adoption is stronger than perceived easy of use (Davis, 1989). This relationship has been further tested by a large number of academics with similar results (Chuttur, 2009). Additionally, efforts have been made to modify the original model by adding more determinants of, for example, perceived usefulness (Venkatesh and Davis, 2000). Further research on the adoption of specifically DSS highlights the importance of user participation which can lead to increased usage (Alavi and Joachimsthaler, 1992;Igbaria and Guimaraes, 1994;Baroudi, Olson, and Ives, 1986) and increased satisfaction(Baroudi, Olson, and Ives, 1986;Lawrence, Goodwin, and Fildes, 2002).

While some authors argue that a DSS is or can be an algorithm (Khoshnevisan et al., 2020) others state that algorithms can be part of a DSS (Bukharov and Bogolyubov, 2015). The previous mentioned insights can therefore be applied to algorithms in general, if one takes the perspective of Khoshnevisan et al. (2020). Most commonly however, literature makes a distinction between an algorithm and a DSS as an algorithm is used to generate the decisions upon which the end-user can act (Khoshnevisan et al., 2020). An algorithm is therefore a set of rules and/or logic which transforms an input into an output (Yanofsky, 2011). As stated before, algorithms are widely used and therefore has yielded plenty of literature discussing the interaction between humans and algorithms. With regards to the attitude from humans towards algorithms there are two strands of literature; one which states that humans prefer the use of algorithms over human decision-making and the other which states the opposite. The former is referred to as algorithm aversion (Dietvorst, Simmons, and Massey, 2015) whilst the latter is referred to as algorithm appreciation (Logg, Minson, and Moore, 2019). Since these are competing results, it is important to investigate papers which agree with the notion of algorithm aversion for underlying reasons why people tend to avoid algorithms. Papers discussing algorithm appreciation are also worth further investigating as they might provide an explanation on why people tend to use algorithms. In their study where they coined the concept of algorithm aversion, Dietvorst, Simmons, and Massey (2015) found that the human user tends to avoid using an algorithm when they see it fail. In a subsequent research, in order to find a way to overcome algorithm aversion, Dietvorst, Simmons, and Massey (2018) found that people are more likely to use an algorithm, even if it is imperfect, when they can exert some type of control over it. Additional factors which are found to decrease algorithm aversion are prior usage by other people (Alexander, Blinder, and Zak, 2018), well-defined situations (Fuchs et al., 2016), objective tasks (Castelo, Bos, and Lehmann, 2019), no prior negative experiences with the algorithm (Logg, Minson, and Moore, 2019;Prahl and Van Swol, 2017) and learning experience with the algorithm (Filiz et al., 2021). Finally, Hou and Jung (2021) remarks that whether a person favours an algorithm or human output is dependent on the amount of influence assigned to each agent and is therefore based on the way each agent is presented to the decision-maker.

Based on this analysis, one can conclude that it is important to include end-users in the development of a DSS in order to reap its benefits. Furthermore, it highlights the two most important determinants of system usage which is perceived usefulness and perceived ease of use. With regards to algorithms, it is important to account for factors related to algorithm aversion, in order to stimulate the use of an algorithm.

3.2.1 The use of scenario analyses in decision-support systems

As described in the previous section, Hilti currently makes use scenario analyses in order to make capacity related decisions. The term scenario analyses is often interchanged with "what-if" analyses and is sometimes included in decision-support systems. In literature, the use and usefulness of what-if analyses in decision-support systems has received limited attention combined with ambiguous results. The proponents for using what-if analysis find that the performance of the decision-maker increases when using the what-if analysis incorporated in DSS compared to not using what-if analysis (Sharda, Barr, McDonnell, et al., 1988;Yuen and Davis, 1997). On the other hand, Kottemann and Remus (1987) found a contradicting result where the performance of the users of the what-if analysis was significantly worse than the users who did not use the what-if analysis. However, the authors argue that a what-if analysis can in fact be beneficial for decision-makers who have limited experience with the context at hand. More experienced decision-makers however, might find adverse effects of using what-if analyses as their tacit knowledge might be superior compared to the rigid set of rules employed by the what-if analysis. The latter is further corroborated by Davis, Kottemann, and Remus (1991) and Davis and Kottemann (1994) as they state that a decision-maker might be overly confident in the output of the what-if analysis due to their ability to adjust parameters, also referred to as 'illusion of control' (Langer and Roth, 1975). The former study concluded by finding no significant positive nor negative effect of decision-making using what-if analyses.

Literature regarding the effective use of what-if analysis is limited (Golfarelli, Rizzi, and Proli, 2006). The authors state that this is due to the fact that 1) there are limited options available 2) the actual design of an application is very complex and 3) there is no clear guideline on designing such an application. In order to add to this gap in the literature, the authors propose a 7-step methodology which details the design of such an application. This research has been further extended by Golfarelli and Rizzi (2010) who provided a way to formalize the model to make it more tangible. When using such models, information transparency is key as the decision-maker should know both how the scenarios are derived as well as the impact of each scenario on the aspects under consideration (Gavanelli et al., 2012). Further things to note is that a structured and rational what-if analysis can benefit the decision-maker by providing the means to consider more information in their decision (Philippakis, 1988). The authors also note that the what-if analysis helps the decision-maker in overcoming an initial preference for a certain decision. The latter was however disputed by a study by Ward (2000), who found that the initial preference of a decision-maker did not significantly influence the final decision. Even though the decision-maker can consider more information, this can also be viewed as a drawback as the decision time will be longer (Yuen and Davis, 1997;Kottemann, Davis, and Remus, 1994). Other techniques, such as optimization, are faster in finding an optimal solution since they explicitly account for restrictions which is not the case with what-if analyses (Roy, 1987). On the other hand, what-if analyses can be useful in situations where there are multiple objectives which can be maximized (Nguyen et al., 2018;Warren, 2012). The effectiveness of what-if analyses can be further increased by developing a suitable user interface where the relevant information is graphically displayed in a structured manner for the decision-maker (Yuen and Davis, 1997).

This subsection has so far detailed the use of scenario analyses in DSS but not specifically related to S&OP decision-making. As stated in the previous subsection, DSS can or should be a vital part of the S&OP process (Grimson and Pyke, 2007;Bharadwaj, 2018;Ávila et al., 2019). The actual implementation of scenario analyses for S&OP decision-making has received limited attention. It can be argued however, that scenario analyses can be useful for S&OP decision-making when implemented properly (Warren, 2012). The author argues that scenario analyses are a viable method for decision-making as it can incorporate the inherent uncertainty of the S&OP process. However, the author adds that in order to make scenario analyses effective, the most important part of scenario analyses in S&OP is that results can be quickly obtained when the environment changes. As uncertainty plays a key role in the S&OP process, it is essential to incorporate this in the scenario analyses model. One approach, as suggested by Schlegel and Murray (2010), calls for a probabilistic predictive approach. This approach consists of creating scenarios based on a deterministic model and supplementing the output of the model with probability of occurrence. On the other hand, one can incorporate the uncertainty directly into the model and thus creating a stochastic model which is highlighted by Sodhi and Tang (2011). The method further uses scenario aggregation which the authors deem necessary as considering all scenarios would be computationally challenging. Overall, it can be concluded that the use of scenario analyses for S&OP decision-making can yield significant benefits, most notably due to the inherent complexity and the multi-objective nature of the decision. However, the model should be carefully designed which includes transparency, a well-organized interface and timely output in order to maximize the benefits.

3.3 Place of thesis in literature

As stated in section 1.5, the main deliverable of this thesis is a decision-support tool. Therefore, one part of this thesis will be related to literature regarding decision-making models in the S&OP process. For such a model, a solid foundation will be build based on either a mathematical model (such as Vargas de Kruif, 2020) or a heuristic (such as Wang, Hsieh, and Hsu, 2012). One key aspect of the model will be the integration of scenario analysis. This aspect will be incorporated at the front-end which facilitates interaction with the CP. In doing so, a new approach will be provided which aims to fill the gap identified by Pereira, Oliveira, and Carravilla (2020). Thus, the primary focus of this thesis with regards to literature is an integrated decision-making tool.

Additionally, the author recognizes that there is a call for comprehensive performance management. Although there are plenty of key performance indicators prescribed by literature (see Hulthén, Näslund, and Norrman, 2016), a comprehensive way of measuring performance is still lacking. This thesis aims to provide a holistic approach of measuring performance which combines relevant indicators of all departments affected by the S&OP decision. Based on empirical tests with the model, the research into the benefits and drawbacks of DSS can be expanded. Furthermore, the method and model developed in this thesis can be used as inspiration to further refine the currently available maturity models (such as Grimson and Pyke, 2007).

Finally, the ultimate goal of decision-support tool is that it is integrated successfully. Successfully in this context can be defined as 1) it quantifiably adds value to the S&OP decision-making process and 2) it is used in practice. The latter is obvious as there is no point in developing a tool that will not be used. Whilst obvious, this is important to recognize which is why one should account for the factors related to technology adoption and related to this, algorithm aversion. To the author's knowledge there is no literature regarding the adoption of DSS in an S&OP context which explicitly accounts for the barriers for adopting such a system also related to algorithm aversion. A visual representation of the place of the thesis within the literature can be found in figure 5.

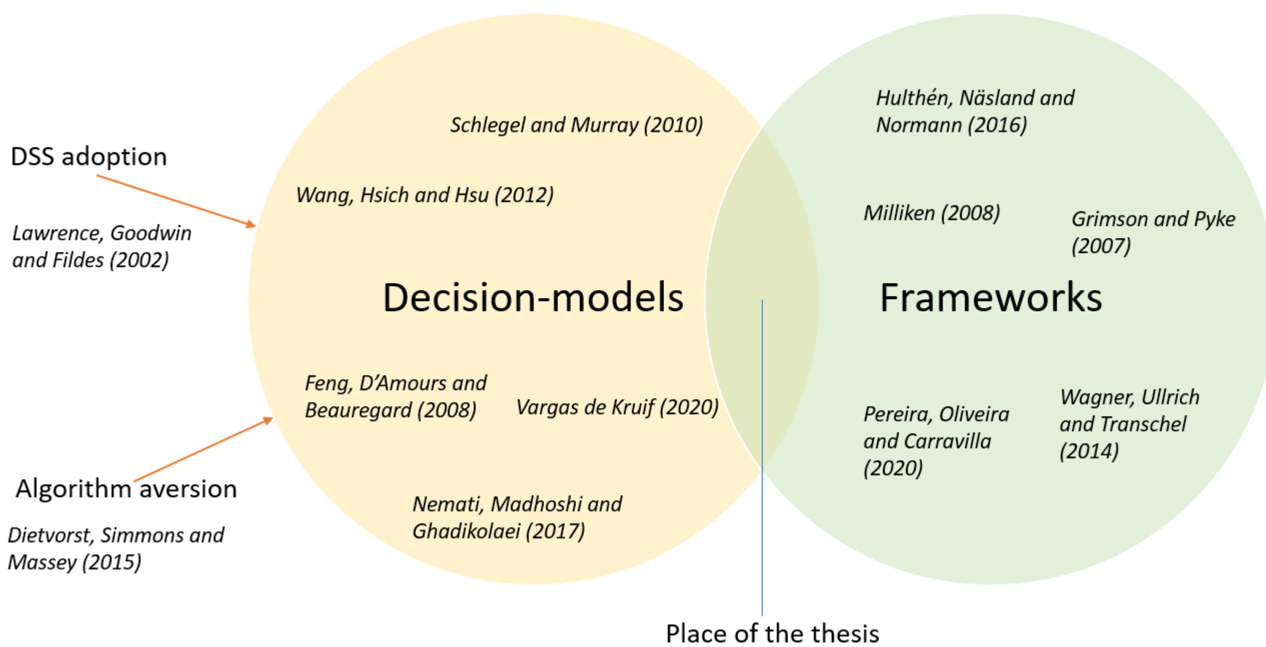


Figure 5: Research area of thesis with respect to current S&OP literature

4 Conceptual model

With the knowledge gained from the literature review and the interviews within Hilti, the relevant concepts can be presented. Based on these interviews, an answer can be provided to the first three subquestions posed in subsection 1.4. The additional information provided by the literature can be used to further refine and complement the base model. In order to structure this section, four subsections are identified. The first three subsections relate to the S&OP process and are the input, the capacity planning and the output. Each subsection highlights variables, information and decisions which are relevant for the CPs in each of these steps within the aforementioned scope of this project. It should be noted that, although different steps are distinguished, the decision-making process is not sequential. For instance, decisions made in the capacity planning step are dependent on the decisions made in the input and output steps. This observation is important to make as one has to realize the intricate nature of the entire decision-making process due to these interdependencies. This section can be concluded by providing an overview of all relevant variables, information and decisions within the scope of this project which in turn forms the basis of the conceptual model.

4.1 Input

In order to determine what the relevant input is, it is important to reiterate the context in which this project takes place. The ultimate goal is to balance the supply and demand in order to achieve a certain objective. The definitive decision on how this balance should be struck is made by the CP. It is important to note here that this decision cannot be made in isolation and is essentially based on the sum of decisions made on various factors which can be influenced. From the description provided in subsection 1.2, it became evident that the demand side is first determined by means of statistical forecast. This is further fine-tuned by market intelligence and translated into the net requirements. Therefore, from the CPs perspective, the input to their decision-making process is the net requirements. Whilst the net requirements cannot be altered, the production plan made by the CPs to fulfill the net requirements can. Therefore, the production plan is the first factor which can be altered.

Initially, the net requirements are synonymous to the production plan as no adjustments have been made yet. However, the CP can opt to either increase, decrease or keep the production plan the same. In doing so, the following information is relevant to consider:

- Forecast bias. The forecast bias provides an indication on the accuracy of the forecast. Since the net requirements are directly derived from the forecast, it also reflect on the accuracy of the net requirements. If there is a significant forecast bias, the CP might consider producing lower or higher than the net requirements depending on the magnitude and direction of the forecast bias.
- Current inventory of end-products. Since the net requirements do not incorporate current inventory, it is important for the CP to steer the production plan accordingly. A significant back-log of end-products can result into the decision to adjust the production plan upwards to ensure order fulfillment. On the other hand, a significant inventory of end-products might result into a production plan which is lower than the net requirements.
- Future net requirements. As mentioned before, the CP usually considers a time horizon of 1-4 months when determining the production plan for the next month. It is important to do so as the production plan for the next month impacts the production plan of future months as well. For instance, the net requirements for month 2 might be higher than the resources available to produce these net requirements. To avoid potential loss of sales, the CP can opt to pre-produce the discrepancy between the net requirements and resources one month in advance assuming there are sufficient resources. This way, the cumulative resources over multiple periods are balanced such that the cumulative net requirements can be met.

Summarizing, the CP receives the net requirements as their main input. Since the net requirements cannot be changed, the CP aligns the production plan as closely to the net requirements as possible. In doing so, it is important to take into account the forecast bias, the current inventory of end-products and the future net requirements. Based on this knowledge, the CP can already decide on a preliminary production plan which fits the net requirements and incorporates the previously mentioned factors. However, to realize this production plan, the CP has to make sure that the resources required to fulfill this production plan are available.

4.2 Capacity planning

In this subsection the resources required to fulfill the production plan are discussed. For this context, three main resources have been distinguished. These resources have been agreed upon to be relevant by the stakeholders involved and are in accordance with the work of Vargas de Kruif (2020). These resources are material, labour and machine. It is essential that all of these three resources are well balanced as production can only happen if all of these resources are present. Discrepancy between these resources are unwarranted as excess of at least one resource, for example material, leads to unused inventory. With the preliminary production plan in mind, it is therefore important for the CP to know the current and future state of these resources and what actions are at their disposal to adjust accordingly.

4.2.1 Material

Material in this context should be interpreted as the components or raw materials which directly go in the end-product. In different words, it is the first layer of the BoM. Previous research by Wagemakers (2022) already showcases the complex nature of the BoM for each end-product. Since the CP makes decisions on an aggregate level, it is important to highlight the most relevant information without introducing unnecessary complexity. It is for this reason that only the first level of the BoM is chosen instead of the entire BoM. The materials can be produced in-house (at the same plant), internal (at Hilti but a different plant) or external. Specific for material, the following information is relevant to consider in making decisions:

- Current inventory of material. The inventory of materials should be as close to the predetermined safety stock as possible. Furthermore, the inventory of each specific material should be as closely synchronized as possible since one can only produce an end-product if all direct materials are available. Insufficient material whether it be a specific material or all of the materials (due to, for example, high net requirements) might result in the CP taking actions to ensure sufficient material is available.
- Pipeline inventory. Whereas the previous point is related to the physical inventory on hand, the pipeline inventory is also important to consider. This is the material that is ordered in a previous period of time and is currently in-transit to the plant. The pipeline inventory and the physical inventory together constitute the inventory position which is a more accurate depiction of the available material. A high inventory position could lead to a decision from the CP to reduce the lot size for the next month(s).
- Levelled material requirements. As stated before, the CP usually considers a time horizon of 1-4 months when making the production plans. Consequently, there is a brief period of time between the decision of the production plan for next month and the effectuation of the production plan (y in figure 6). In this brief period of time, materials are being used according to the production plan of that period. As a result, at the point of making the decision for next month, the usage of this material is not considered as it is still part of the current inventory. It is therefore important that, when determining the quantity of material required, the CP subtracts the materials used for the production of the remainder of the month from the current inventory level. This results in the levelled material requirements. A visualization is provided in figure 6.

- Lead time. When ordering additional material, it is important to know when it arrives. Since different materials have different lead times, it is crucial to streamline this process to avoid unnecessary warehouse occupation for materials with shorter lead times. Furthermore, the lead time dictates the ability to receive materials on time. Therefore, the lead time should be known and accurate in order for the CP to make timely decisions such that the production plan can be realized.
- Production availability (PA) score. The PA score is a score assigned to external suppliers which indicates their reliability in delivering the correct quantity ordered in the agreed-upon time frame. The higher the score, the more reliable the supplier. It is important to keep this score in mind when ordering material since one can closely monitor those materials ordered at a supplier with a low PA score and take timely measures if necessary.

One can also argue that is important to know component information. For instance, if historic data shows that a component was not available in a certain time period, one might consider increasing the lot size prior to this period to avoid potential stock-out. Whilst this reasoning could be valid, one should only do this if the root cause of the unavailability can be determined. For example, the supplier might always have issues in this specific period due to seasonal demand for the component. In this case, it might be wise to increase the lot size prior to this period as the issue might reoccur. On the other hand, it could also be that the supplier had a smaller workforce than they expected due to sickness. In this case, it is highly unlikely that this happens again in the same period which means increasing the lot size before this period might lead to unnecessarily high inventory levels. This example illustrates the importance of recording this information such that future decisions about order materials can be made more accurately. Unfortunately, this information is not recorded which means that historic data does not provide a reliable indication of potential stock-out.

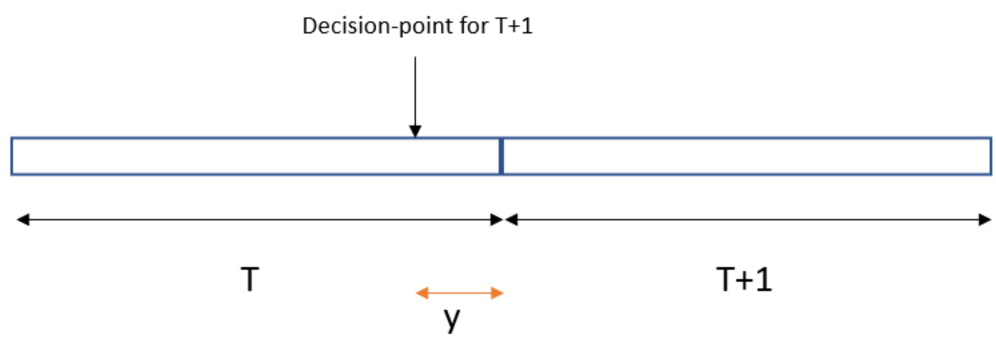


Figure 6: Illustration of unaccounted inventory being used in the remainder of period T (y) after making material decision for period T+1

Based on the aforementioned information the CP can decide to make adjustments to the quantity of materials at their disposal for the next (few) month(s). They can do so by doing the following:

- Change lot size. Depending on the current inventory position and the production plans in the next few months, the CP can decide to adjust the lot size accordingly. A relatively low inventory position compared to the preliminary production plan might invoke the CP to adjust the lot size in an upward direction to prevent a potential lack of material in the future. Whether the CP can exercise this option depends on two factors. The first factor is the agreed-upon contract with the supplier. For example, if Hilti has a fixed monthly quantity contract with a supplier, the CP cannot expect the the material quantities to be adjusted. The second factor is related to the moment of decision-making of the CP. If the CP identifies that additional material is required for the next month, due to lack of time for the supplier to produce this additional material, it may not arrive in time. Therefore, when making adjustments to the lot sizes, it is important to consider this time aspect.

- Transshipment of material. Transshipment of material can take place if a different warehouse location has excess of a material which the CP requires. In this case, the CP can order from the other warehouse location to have the material shipped to the desired location.
- Partial shipments. When a CP requires additional material and the supplier cannot fully fulfill the order, the CP can ask for partial shipments. In this case, the supplier supplies the maximum quantity of what they can supply instead of supplying nothing such that at least a part of the production plan can be fulfilled. This option is often exercised when the supplier cannot deliver the agreed-upon quantities.

Highlighting the potential actions a CP can take also reveals the actions a CP cannot take which are important to briefly discuss:

- Buy additional material on the spot market. In literature, an often mentioned action is to buy a missing component for a premium price on the spot market. For Hilti however, this is not an option that is exercised often. The main reason is that the components have to adhere to the quality standard set by Hilti. Ensuring that a substitute component from a different supplier meets these standards is a long process and is therefore not viable as a short-term solution. Furthermore, the components used in Hilti products are often Hilti specific. As a result, there are no other companies which are making this component as there is only one supplier manufacturing a specific component. An exception to this rule is bulk stock; such as screws and bolts. In these instances, the spot market can be considered but it does not occur often that these types of items are facing stock-out issues. For these reasons, the option to buy components at the stock market is not considered.
- Sell excess material. Whilst the previous option discusses a potential solution in situation where there is lack of material, the opposite can also occur. In a situation with excess material, one might consider the option of reselling the material. If possible, one accepts a lower price for the material in order to save on inventory costs. However, in practice, Hilti cannot exercise this option as 1) the supplier does not accept the return of the material and 2) there is no market for most of the material as they are often Hilti specific.

From this analysis, it becomes clear that there are many factors to account for when making material decisions. Whilst there are many factors which are relevant, the concrete actions a CP can take to adjust material quantities are limited. This is further amplified by the fact that the actions are bound by time which further highlights the importance of proactive decision-making.

4.2.2 Labour

The resource labour is interpreted as the manpower required to manufacture the end-products. As stated before, the manufacturing of end-products can be done by either workers (assembly) or machines. In either case, labour is required as machines require operators to function effectively. The following information is relevant for the CP to consider when making adjustments to the labour capacity:

- Capacity corridors. The capacity corridors define the upper and lower bound in which the labour hours can be adjusted. These bounds cannot be exceeded as they are bound by regulations and contracts. If the CP wants to make adjustments to the labour hours used for a period, they should do so within these bounds. It should be noted that these corridors are therefore often region specific which means that if a CP operates in multiple regions, they have to account for different regulations.

- Required team size and composition. As stated before, a CP is responsible for making capacity related decisions for production lines which fall in their portfolio. Since each production line produces one or more products, it is often the case that there are different labour requirements within a production line. For instance, one product might be more labour intensive and thus requires a larger team for production. Whilst the required team size can be partially reflected in hours available, it is still important to make this distinction. This is further supported by the fact that operating a production line might require a special operator within the team. This operator possesses a certain skill or capability which is not taught to the entire workforce such as operating a specific machine or the assembly of a specific component. Therefore, it is always important to assess whether there are sufficient workers available with the necessary skills to operate the production line according to the preliminary production plan.
- Production speed. For assembly plants, the production output is solely based on the team working on the production line. It is important for the CP to know how many products per shift hour a team can produce to properly assess the production capabilities.
- Workers' satisfaction. Whilst the latter three points can be expressed in quantitative terms, there are also qualitative factors which are important to consider. With regards to labour, it is important to consider the perspective of the workers. After all, it is important to maintain a pleasant work environment to prevent staff turnover and maintain production rates. Practically speaking, this means that a solution which is theoretically feasible might not be feasible or desired in practice. For instance, in a situation where the CP is lacking regular shift hours for production, the CP can opt for special shifts to cover this gap. Since these special shifts occur during non-regular working hours, workers might show a reluctance to work these shifts even if pay is higher. It is therefore important to assess beforehand whether the use of, in this case, special shifts is actually feasible in practice and leads to the expected results.

With this information in mind, the CP can make certain adjustments to this resource which aligns with the preliminary production plan. These adjustments can be defined as follows:

- Increase/decrease number of shifts. This measure directly relates to reducing or increasing the amount of labour hours available for a period since shifts lengths are predetermined on a plant level. It should therefore be noted that increasing or decreasing the number of shifts in a period yields different results for different plants as the respective hours per shift might differ per plant. Furthermore, since there are different types of shifts, the CP should be aware of the total hours available per shift type as each shift type has a different cost.
- Increase/decrease hours per shift. With the shift duration being known beforehand, a different measure a CP can take is to adjust this duration upwards or downwards. Adjusting the shift duration upwards essentially means that the personnel will be working overtime. Therefore, the CP should carefully consider this option as additional costs will be incurred. Furthermore, this measure is narrowly related to increasing or decreasing the number of shifts. This measure is therefore best exercised when there is a small gap between the hours needed and the current available hours.
- Increase/decrease personnel per shift. Instead of adjusting the hours to obtain the desired production, the CP can also increase the throughput directly by employing less or more workers in the production line. In case of overcapacity, the CP should closely consider the minimum amount of workers required to run a production line as this threshold cannot be exceeded. Furthermore, it is very difficult to exercise this option in practice as the addition or removal of personnel does not scale linearly with production. Therefore, whilst theoretically possible, this option is not often exercised as the benefits of doing so are difficult to quantify.

- Relocate/borrow personnel. These measures can be taken if the current workforce level is higher or lower than required in order to run the production line. When there are more workers available then required for the production line, the CP can attempt to relocate them to a different production line. This can only be done if the workers have the required set of skills and knowledge to work this other production line. Similarly, if there a not enough workers available for production, the CP needs to ensure that additional workers are borrowed from other production lines.
- Train personnel/other work. When the previous options to decrease labour capacity have been exhausted or are not possible, the final two options are to train the personnel or assign them to other work. Therefore, these options are only exercised to prevent idle time. The former is in general beneficial for the company as a whole as the worker will become more dynamic in their ability to work on other production lines. The latter is less beneficial as the worker is doing miscellaneous work which is unrelated to their job description such as, for example, general shop floor cleaning.

It should be noted here that the option to hire and fire personnel is omitted. Although these are often cited methods to reduce or increase labour in literature, these measure are intentionally not included. This is due to the fact that hiring or firing personnel is out of the decision scope of a CP since it has long-lasting consequences beyond just the labour capacity for their production line. In case of long-term overcapacity, the personnel is often relocated or trained. With recurrent undercapacity, the CP can signal that it might be beneficial to hire additional personnel but this will not aid the CP on a short-mid term time horizon.

Contrary to the material resource, it can be seen that the CP has significantly more flexibility with respect to the labour resource. Even though there are more options available, the importance of this resource should not be neglected due to the collective need for all these resources for production. Furthermore, the qualitative aspect of decisions for this resource should not be underestimated as a theoretical intervention might not yield the desired results in practice.

4.2.3 Machine

The third and final resource is machine capacity. As described in section 1.2, Hilti has both assembly and tool plants. The former does not rely on machines and production is solely based on the material and labour resources. Since the model aims to service both tool and assembly plants, the machine resource will be briefly discussed. However, due to the fact that the model aims to be general, specific machine constraints will not be discussed. The following two things are important to consider:

- Maximum available machine hours. Similar to the capacity corridor, the machine(s) which are being used are bound by their maximum run time. This is otherwise referred to as the technical capacity of the production line. Any planned maintenance or known issues are included in this number.
- Throughput. For tool based plants, the output is directly related to the amount of products a machine can make per hour or in other words the throughput. It is essential that the CP is aware of the throughput of the different end-products on their production line to assess their production capability.

With the relevant information in mind, the CP can make the following adjustments to this resource:

- OEE (Operational equipment effectiveness) interventions. OEE interventions are a measure to improve the overall performance of the machine. Practically speaking, an OEE intervention can result in a higher throughput. However, defining these interventions are out of the scope of the CP. Furthermore, the benefits gained from an OEE intervention dependent on the intervention itself. Therefore, a CP might be able to indicate that an OEE intervention might be beneficial but the concrete benefits of such interventions are difficult to quantify.
- Temporary machines. The final measure a CP can take in order to increase or fulfill production is to use temporary machines. Generally speaking, temporary machines are only used in case of long-term full production stops. This is due to the long set-up times of the machines combined with the fact that their use is temporary. For this reason, the use of temporary machines is not considered as a regular measure to increase production.

Based on the previous information, it becomes clear that the options regarding the machine resource are limited. In fact, on a short term, there are no options to increase the machine capacity. This is also due to the fact that the usage of other machines is in practice not feasible. After all, these machines are designed to perform different operations and can therefore not be setup for specific needs. Different machines which can perform the same operations are included in the maximum total machine hours. In practice, the lack of the machine resource is often not the problem with production. However, if there are issues with this resource, there are very limited measures a CP can take to alleviate the issue.

This subsection illustrated how a CP can manage their resources and how that is related to the production plan. The decision of managing the trade-off between potential loss of sales and additional labour, material and machine is ultimately based on the objective the CP wants to fulfill. This objective is discussed in the next subsection; namely the output.

4.3 Output

The previous two subsections provide the foundation of the model namely the demand (Input) and supply (Capacity planning). How to approach the balancing of the demand and supply ultimately comes down to the objective of the CP. After all, the objective coincides with the priorities of the CP. The previous subsection has provided an overview of all possible actions/measures a CP can take in order to increase or decrease resources usage. All of these actions have an impact which can be measured in a monetary value. Therefore, any action taken is either subconsciously or deliberately steering towards the objective of the CP. For instance, the CP can have as an objective to maximize service level. In this case, the CP will use all resources necessary to avoid loss of sales, irrespective of the additional incurred costs. This reveals the key piece of information that is required for making this decision: costs. Figure 7 provides a basic illustration of the trade-off under consideration. Essentially, the green area indicates that the unit cost of lost sales exceeds the marginal cost of production which favours the production of one additional unit. The opposite holds for the orange area. The unit cost of lost sales and the marginal manufacturing costs in this example can be objectively determined by extracting the data from the ERP system. However, these costs can be subjectively altered to account for the CPs priorities. Ultimately, the appropriate cost functions comes down to the context and the corresponding objective of the CP.

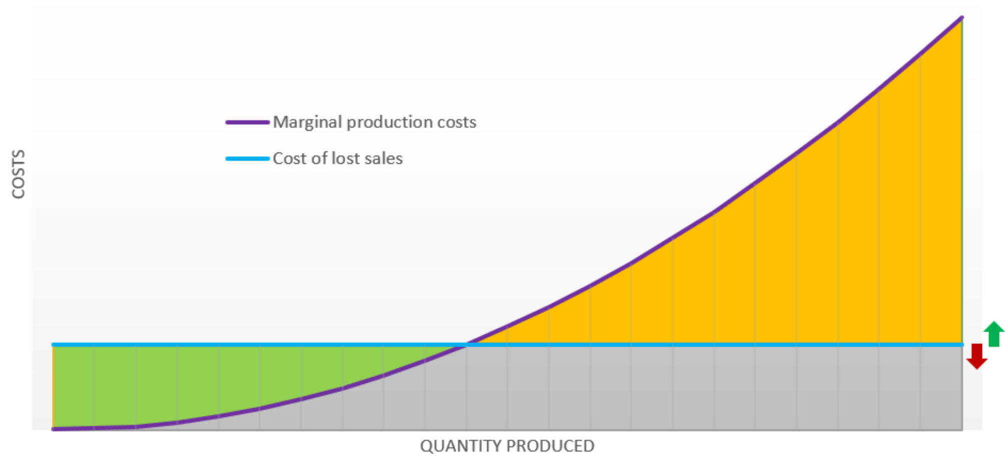


Figure 7: Example of the cost structure in balancing supply and demand

4.4 The conceptual model

With all the steps of the S&OP process within the scope of this project explained and examined, this final subsection combines all this information to fit an appropriate model. From the aforementioned description it becomes clear that the CPs have different decisions based on the time frame they operate in. It is also important to recognize this distinction in the model as it highlights the dual nature of the decision-making process. The model should be functional for both short (reactive) and longer (proactive) time horizons. Furthermore, it is important to account for the granularity of the model. First of, CPs are making tactical decisions. Therefore, the time horizon considered in the model should not exceed 12 months. Additionally, the CPs should take only the information into account which is considered relevant for this context. This means that the CP should not be concerned with the specific operations which underlie their decisions. For instance, a CP can increase the labour resource by increasing the number of shifts. How these shifts are implemented in practice is up to the plants.

The perspective of the CP plays a central role. Therefore, the focus of the model is to determine the impact on the production capabilities instead of the specific scenarios at hand. For example, a specific component cannot be received due to a manufacturing issue at the supplier. As a result, the production for the end-products containing this component comes to a stop. A similar impact can be derived if the lead time of this specific component suddenly increases. Although the scenarios are different, the production capability is affected in the same way. It is important to make this distinction because the previous analysis shows that the predictive capabilities in this context are limited. This is due to the significant amount of uncertainty involved regarding future resource availability and actual demand realization. Furthermore, it was found that the data about past resource issues are often not recorded. As a result, historic data is not indicative of current and future resource availability. For modelling purposes, this reduces the ability to include uncertainty into the model. As a result, the nature of the model should be deterministic instead of stochastic. The deterministic output of the model fits this context well as the CPs want to know the optimal solution in the scenarios they develop. However, in order to create scenarios, the input of the model which is normally retrieved from the ERP system should be adjustable for the CPs.

In order to account for the lack of uncertainty within the model, different ways of including uncertainty into the model have to be devised. After all, the goal is to develop scenarios and assess their impact on the production plan. One way to make sure that the CPs can develop scenarios is to allow for manual intervention. In this way, the model is made dynamic and the CP can manually adjust the value of the input parameters to account for uncertainty. Furthermore, the model should be dynamic in the sense that a CP can determine their own objective as described in section 4.3.

Finally, it is important to recognize the core purpose of the model (and derived tool) which is decision-support. Ultimately, the tool serves as an aid to assist the CP when making the complex trade-offs which are inherent to capacity planning. The tool should be used to either confirm or challenge the CP's intuition and guide the CP in accomplishing their objective. For this reason, the model and resulting tool should be focused on delivering comprehensible and actionable output. In doing so, it is important to find the right balance between complexity and accuracy. After all, an overcomplex model is difficult to operationalize and generalize for different contexts. Furthermore, the model should reduce the decision complexity instead of increasing it. Capturing all the details and therefore accounting for all the complexity might have adverse effects on the decision quality of the CP. On the other hand, the model should still be representative of the environment. Therefore, it is important to add the essential elements into the model to establish an accurate model. However, the functionality of the model remains central and therefore additional complexity is only introduced if it does not significantly impact the practicality and functionality of the model (and tool). A depiction of the conceptual model based on the information provided in this subsection can be found in figure

8.

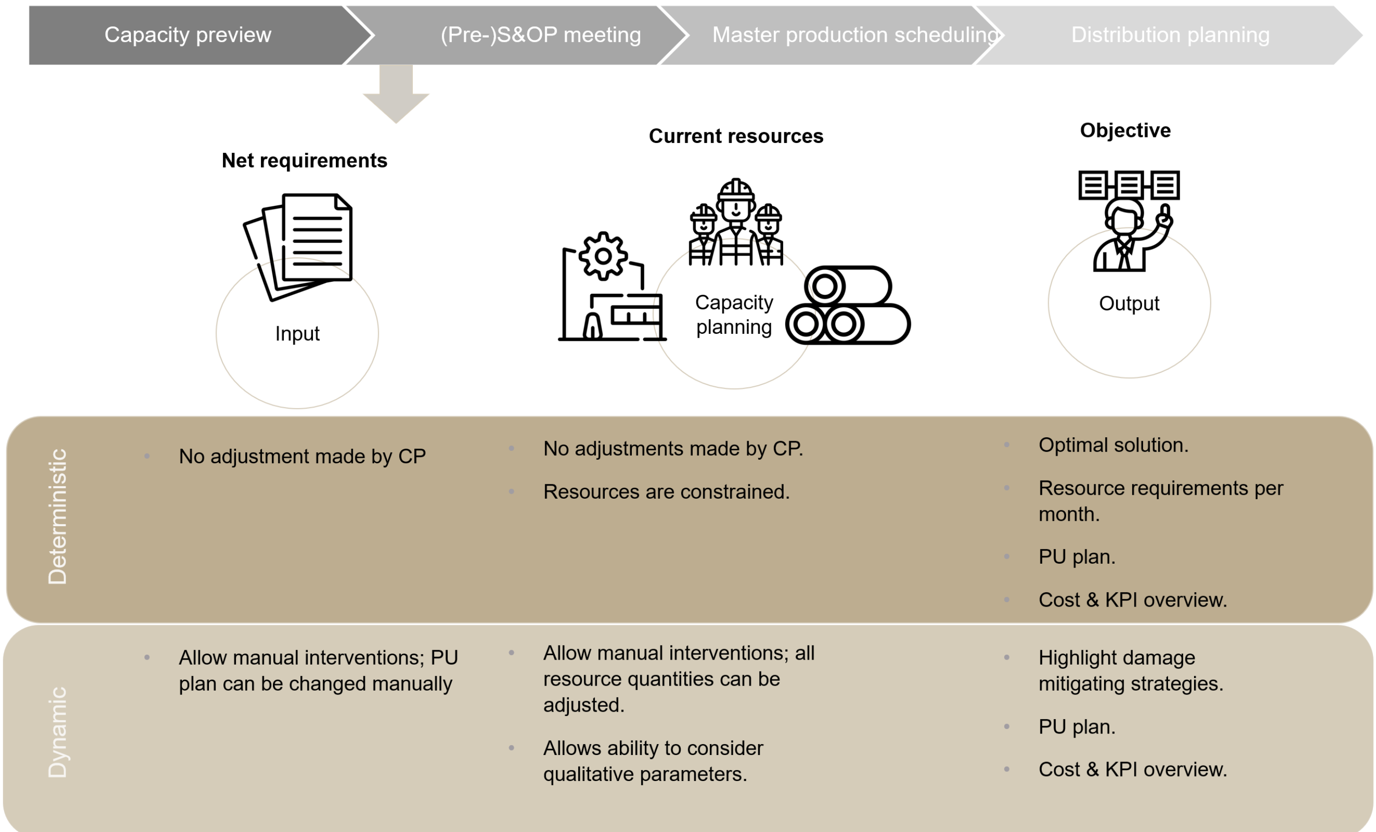


Figure 8: The conceptual model

5 Mathematical model

The previous section has provided the foundation of the model and the way it should be operated. It became evident that there is a need for both a dynamic model and deterministic model. The dynamic model leaves room for the CP to alter the resources in future periods to create scenarios whilst the deterministic model determines the optimal quantity of resources given an objective. A common way to obtain an optimal solution to these types of problems is by means of linear programming. In linear programming, one defines an objective function which is solved to optimality based on a set of constraints. Within linear programming, one makes a distinction between parameters and decision variables. Parameters are predetermined values which are unaltered by the program. On the other hand, decision variables represent the values which can be adjusted such that optimality can be reached. Therefore, the output of a linear program contains the optimal value for the objective function as well as the values of the decision variables. The purpose of this section is to formalize the decisions and information provided in the previous section such that it is fitted in the form of a linear program.

5.1 Single production line

The goal of this first subsection is to provide an initial model which can be used as a starting point for each production line in each plant. Therefore, current interdependencies (such as shared labour for example) will be omitted from this model. This subsection is setup as follows. First, the relevant planning horizon will be discussed. After that, the relevant decision variables and parameters will be highlighted per resource (material, labour and machine). Based on that information, the objective function will be presented. As stated before, the objective function is dependent on the goal of the CP so two alternatives will be presented. Subsequently, the relevant constraints will be provided. This subsection will be concluded by discussing the assumptions of the generic model.

5.1.1 Planning horizon

Before the model is introduced, it is important to define the planning horizon. From the description in subsection 1.2 and the additional knowledge gained from literature, it was determined that one can categorize the S&OP decision-making process as a tactical decision. However, even within the realm of tactical decision-making there is still a significant amount of ambiguity as there is no consensus about the specific time horizon of such decisions. It is therefore important to further look at the context at hand and fit the planning horizon to the purpose of the model.

With the context in mind, it is opted to initially consider a six month planning horizon for the model. This choice is made based on the following reasons. First, in the (pre-)S&OP meetings within Hilti, the CPs consider a time horizon of 1-4 months when making their decisions. Since the tool is meant to assist in this consideration it should include at least this time period. The reason to include six months instead of four is to provide the consequences in month five and six if the CP foresees an issue in month four. It should furthermore be highlighted that the model will be implemented in a decision-support tool. This tool should provide a concise overview of the most relevant information for the CP. Therefore, increasing the number of months which can be considered increases the complexity for both the decision-making process of the CP as well as the visual representation of the model in the tool. Finally, increasing the planning horizon further adds complexity to the model. As mentioned before by Warren (2012), the decision-maker should be able to receive timely feedback from the tool when adjustments are made, which in this context is alternative scenarios considered.

Ultimately, the time horizon considered for the model can be adjusted in an upward or downward direction. For the remainder of this report however, the planning horizon will be six months. Furthermore, unit of time in this context will be months as the capacity planning is done on an aggregate level. For the mathematical model, the time variable will be denoted as t with $1 \leq t \leq 6$.

5.1.2 Labour

The first resource which will be discussed is labour. This section will detail first the parameters related to the cost of labour. After that, the other relevant parameters will be highlighted which are related to the context as depicted in the conceptual model. This section will be concluded by highlighting the relevant decision variables. It should be noted that for this resource, a lot of work has already been performed by Vargas de Kruif (2020). For this reason, the same parameters and decision variables will be used where applicable.

Parameters

Table 2 showcases the costs relevant for labour. Compared to Vargas de Kruif (2020), two extra types of hours are identified in Sunday and holiday hours. One should note here that the costs are of a quantitative nature. This means they do not account for the additional information a CP has. In the conceptual model, it was made clear that it is important for the CP to account for the worker's satisfaction. Since the model does not account for this factor, it might generate a solution which is feasible on paper but infeasible in practice. To account for this, and other qualitative aspects, these costs can be augmented by the CP to provide a more accurate depiction of reality. Since the preferences of worker's are different for different plants, there is not one unambiguous value which can replace the actual cost to incorporate these qualitative aspects. Therefore, if the CPs do want to account for these qualitative factors, it is suggested to multiply the actual cost with a constant to achieve a representative cost:

$$Cost(Qualitative) = Cost(actual) * factor, \quad factor \geq 1 \tag{1}$$

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Parameters related to labour − Costs		
Cost	*Definition*	*Notation*
Regular shift cost	Cost of regular labour hours (08:00-00:00)	*CDS*
Night shift cost	Cost of night labour hours (00:00-08:00)	*CNS*
Saturday shift cost	Cost of Saturday labour hours	*CSA*
Sunday shift cost	Cost of Sunday labour hours	*CSU*
Holiday shift cost	Cost of labour hours on holiday days	*CHO*
Extended shift cost (regular)	Cost of extra shift hours per shift (08:00-00:00)	*CEXD*
Extended shift cost (night)	Cost of extra shift hours per shift (00:00-08:00)	*CEXN*

Table 2: Overview of relevant cost parameters related to labour

Table 3 showcases the other relevant parameters for labour. Once again, the parameters are derived from the conceptual model and corroborates the parameters used by Vargas de Kruif (2020). One can see a clear distinction between the type of parameters. First, for every type of shift, the amount of work hours are determined. This number can range between the 0 and 8 hours and is usually set to be 8 hours for regular working days. However, this parameter can be altered accordingly. After that, the number of working days within the month is determined. For example, December will have a significantly more holiday days than November. This together provides the foundation for the total available hours per month. Moreover, the number of workers is provided which determines the production capability of the production line. To ensure that the production hours are within the legal limits, the parameters L_t^{max} and L_t^{min} are setup. To provide more structure to the work hours, the parameter $S_{i,t}$ is introduced. This parameter indicates the type of shift model (i) in month t. The main purpose of this parameter is to structure the hour assignment into logical timeslots. After all, employees work according to a shift schedule. After this shift model is chosen, the adjustments such as extend or reduce shift hours can be applied. From this description it becomes clear that the shift model is a binary variable and therefore $S_{i,t} \in (0, 1)$. Although a shift can take any arbitrary value, the most appropriate shift length in this context is 8 hours. Therefore, the shift model can either be 1 shift per day, 2 shifts per day or 3 shifts per day. The latter automatically suggest that a night shift is incorporated. From this description it is therefore made clear that i is either 1, 2 or 3 for any $t \in T$. In order to bridge the gap between resource material and labour hours, the parameter K_e is introduced. This parameter details the number of end-product e which can be made in one shift hour. It should be noted here that a production line can only function with a set amount of workers (team). Therefore, increasing the amount of workers will not increase K_e. The required team size for a specific end-product is depicted as TS_e, where

$$1 < i * S_{i,t} * TS_e \leq W_t + exp_t \quad \forall i \in I, e \in E, t \in T \tag{2}$$

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Parameters related to labour – other		
Parameter	*Definition*	*Notation*
Workforce level	Number of workers in month t	W_t
Work hours per shift (morning)	The amount of work hours per shift (06:00-14:00)	WD
Work hours per shift (afternoon)	The amount of work hours per shift (14:00-22:00)	WA
Work hours per shift (night)	The amount of work hours per shift (22:00-06:00)	WN
Work hours per shift (saturday)	The amount of work hours per shift (saturday)	WSA
Work hours per shift (sunday)	The amount of work hours per shift (sunday)	WSU
Work hours per shift (holiday)	The amount of work hours per shift (holiday)	WHO
Working days (regular)	The number of regular working days in month t	AD_t
Working days (Saturday)	The number of workable Saturdays in month t	ASA_t
Working days (Sunday)	The number of workable Sundays in month t	ASU_t
Working days (Holiday)	The number of workable Holidays in month t	AHO_t
Maximum extended hours (morning)	The maximum number of hours which can be used to extend a morning shift in month t	$HEXD_t^{max}$
Maximum extended hours (afternoon)	The maximum number of hours which can be used to extend an afternoon shift in month t	$HEXA_t^{max}$
Maximum extended hours (night)	The maximum number of hours which can be used to extend a night shift in month t	$HEXN_t^{max}$
Maximum decreased hours (morning)	The maximum number of hours which can be used to decrease a morning shift in month t	HLD_t^{max}
Maximum decreased hours (afternoon)	The maximum number of hours which can be used to decrease an afternoon shift in month t	HLA_t^{max}
Maximum decreased hours (night)	The maximum number of hours which can be used to decrease a night shift in month t	HLN_t^{max}
Maximum labour hours	The maximum number of labour hours in month t	L_t^{max}
Minimum labour hours	The minimum number of labour hours in month t	L_t^{min}
Shift model	The type of shift model (i) employed in month t	$S_{i,t}$
Conversion factor	Amount of end-product e made per shift hour	K_e
Team size	The amount of people required to run the production line for end-product e	TS_e
Maximum number of borrowed workers	The maximum number of additional workers available in month t	EXP_t^{max}

Table 3: Overview of other parameters related to labour

Decision variables

The decision variables for labour can be found in table 4. Most of the decisions are self explanatory and based on the conceptual model and the mathematical model of Vargas de Kruif (2020).

Decision variables related to labour		
Decision variable	*Definition*	*Notation*
Additional workers	Number of workers borrowed from a different production line in month t	exp_t
Workday hours assigned (morning)	Hours assigned to morning shifts in month t (06:00-14:00)	hds_t
Workday hours assigned (afternoon)	Hours assigned to afternoon day shifts in month t (14:00-22:00)	hda_t
Workday hours assigned (night)	Hours assigned to night day shifts in month t (22:00-06:00)	hns_t
Saturday hours	Hours assigned to Saturday shifts in month t	hsa_t
Sunday hours	Hours assigned to Sunday shifts in month t	hsu_t
Holiday hours	Hours assigned to holiday shifts in month t	hho_t
Extended morning shift	Additional hours assigned to a morning shift (06:00-14:00)	$hexd_t$
Extended afternoon shift	Additional hours assigned to a day shift (14:00-22:00)	$hexa_t$
Extended night shift	Additional hours assigned to a night shift (22:00-06:00)	$hexn_t$
Reduced day shift	Decrease of hours assigned to a morning shift (06:00-14:00)	hld_t
Reduced day shift	Decrease of hours assigned to a afternoon shift (14:00-22:00)	hla_t
Reduced night shift	Decrease of hours assigned to a night shift (22:00-06:00)	hln_t
Idle time	Excess of shift hours in month t	hi_t

Table 4: Overview of decision variable related to labour

5.1.3 Material

Parameters

The next resource which will be discussed is material. Similar to labour, the cost parameters are first discussed which can be found in table 5. As one can see, three main costs are distinguished. First, the purchasing price of a specific component which is required for production of the end product. Second, the cost of lost sales. It should be noted here that there are two different values for this cost. As discussed in the conceptual model, the model should be able to calculate the cost based on the goal the CP wants to achieve. The parameter M is introduced to account for the goal of maximizing service level where M represents a big number and thus $M \geq CLS$. Finally, the cost of keeping inventory are relevant. A distinction is made between end-products and components as they have different inventory cost per unit. Furthermore, it was found that components can be either stored internally, externally or at the docks. The latter means that the components are still in containers at the docks due to lack of external and internal storage space. From this description is can also be concluded that end-products cannot be stored at the docks as they are outbound goods. Therefore, $CIC_c^{dock} \geq CIC_c^{ext} \geq CIC_c^{int}$.

Parameters related to material – Costs		
Cost	*Definition*	*Notation*
Component cost	Purchasing price of component c	CPU_c
Cost of lost sales (regular)	Cost of 1 unit of unfulfilled demand	CLS
Cost of lost sales (Maximize service level)	Cost of 1 unit of unfulfilled demand (Max service level)	M
Cost of end-product inventory (internal)	Cost of keeping 1 unit of end-product e inventory locally	${CI_e}^{int}$
Cost of end-product inventory (external)	Cost of keeping 1 unit of end-product inventory externally	${CI_e}^{ext}$
Cost of component inventory (internal)	Cost of keeping 1 unit of component c in inventory locally	CI_c^{int}
Cost of component inventory (external)	Cost of keeping 1 unit of component c in inventory externally	CI_c^{ext}
Cost of component inventory (docks)	Cost of keeping 1 unit of component c in inventory at the docks	CI_c^{dock}

Table 5: Overview of cost parameters related to material

Table 6 highlights the other relevant parameters for material. As mentioned before, there are different types of storage options for inventory. All these storage options have maximum capacities as highlighted by the first five parameters. Moreover, the starting inventory for both end-products and components have to be established such that the inventory constraints, which are discussed later, can be properly formulated. Furthermore, as mentioned in the conceptual model, the amount of components ordered per month is often constrained by the established contract with the supplier. This in turn results in the parameters $E_{c,t}^{min}$ and $E_{c,t}^{max}$ which showcase the minimum and maximum order quantity per month respectively. It is important here to note that this is on a monthly basis. If, for example, the CP foresees an increase in production in month $t+2$ which goes beyond $E_{t,c}^{max}$, the material manager might negotiate with the supplier to increase $E_{t,c}^{max}$ in month $t+1$. Furthermore, the production coefficient ($B_{c,e}$) is introduced to bridge the gap between components and end-products as this parameter shows the amount of one specific component required for the production of unit of the end-product.

Parameters related to material – other		
Parameter	*Definition*	*Notation*
End-product storage capacity (internal)	Maximum quantity of end-product e which can be stored internally	${SE_e}^{intmax}$
End-product storage capacity (external)	Maximum quantity of end-product e which can be stored externally	${SE_e}^{extmax}$
Component storage capacity (internal)	Maximum quantity of component c which can be stored internally	SC_{cc}^{intmax}
Component storage capacity (external)	Maximum quantity of component c which can be stored externally	SC_{cc}^{extmax}
Component storage capacity (docks)	Maximum quantity of component c which can be stored at the docks	$SC_{cc}^{dockmax}$
Starting end-product inventory (internal)	The amount of end-product e in internal storage at time t=0	SIE_e^{int}
Starting end-product inventory (external)	The amount of end-product e in external storage at time t=0	SIE_e^{ext}
Starting end-product backlog	The amount of end-product e in backlog at time t=0	SB_e
Starting component inventory (internal)	The amount of component c in internal storage at time t=0	SIC_c^{int}
Starting component inventory (external)	The amount of component c in external storage at time t=0	SIC_c^{ext}
Starting component inventory (docks)	The amount of component c in storage at the docks at time t=0	SIC_c^{dock}
Minimum order quantity	Minimum order quantity of component c in period t	$E_{c,t}^{min}$
Maximum order quantity	Maximum order quantity of component c in period t	$E_{c,t}^{max}$
Production coefficient	Number of component c required for production of 1 unit of end-product e	$B_{c,e}$

Table 6: Overview of other relevant parameters related to material

Decision variables

The relevant decision variables for material can be found in table 7. As for every relevant resource, the first decision variable highlights the amount of component c which is bought for production at time t. The remaining decision variables concern the assignment of components and end-products to the available storage locations.

Decision variables related to material		
Decision variable	*Definition*	*Notation*
Material requirement	Amount of component c bought at time t	$mr_{c,t}$
Inventory end-product (internal)	Amount of end-product e stored internally at time t	$ie_{e,t}^{int}$
Inventory end-product (external)	Amount of end-product e stored externally at time t	$ie_{e,t}^{ext}$
Inventory component (internal)	Amount of component c stored internally at time t	$ic_{c,t}^{int}$
Inventory component (external)	Amount of component c stored externally at time t	$ic_{c,t}^{ext}$
Inventory component (docks)	Amount of component c stored at the docks at time t	$ic_{c,t}^{dock}$

Table 7: Overview of other relevant decision variables related to material

5.1.4 Machine

From the conceptual model, it became clear that the options with regards to increasing and decreasing machine capacity are limited. OEE improvements remained the only viable option to potentially increase the throughput but this is not a decision made by the CP. Furthermore, it is difficult to quantify the impact of OEE on the throughput of the machine as the measures taken are context-specific. It is therefore concluded that the machine capacity should be considered as a hard constraint which cannot be adjusted by the CP. Due to the limited influence there are only two parameters identified namely:

- Throughput, which is the number of end-product e which can be produced by a machine per hour (R_e).
- Maximum capacity, which is the maximum hours in month t a machine can produce also referred to as the technical capacity (HM_t^{max})

For this resource, no decision variable is relevant. One can argue that the amount of machine hours used per month is a decision variable. However, since there are no costs attached to increase or decreasing the machine hours, the value of this decision variable is considered to not be relevant.

5.1.5 Global decision variables and parameters

Parameters

In this final subsection, the parameters and decision variables are discussed which do not specifically fall in any of the resource categories. This parameter relates to the actual production plan. As stated before, the actual production plan should be based on the net requirements and therefore the parameter $NR_{e,t}$ is introduced.

Decision variables

To conclude the decision variables in the model, the final decision variable $p_{e,t}$ is presented. The production quantity ultimately determines how much of product e is produced in month t, which accounts for the previously mentioned parameters. It should be noted here that the production plan can only be as high as the lowest value of the resources available in that period.

5.1.6 Objective function

With the aforementioned decision variables and parameters defined, the objective function can be determined. As stated before, the objective function can be decided by the CP depending on which goal they want to achieve. There are two main goals selected for this model namely maximize service level and minimize cost. These two goals are selected as they are the most common objectives in practice and the formulation is identical. The only difference in model formulation is the value of the cost parameter lost sales. For the minimize cost objective function this value is *CLS* whilst for the maximize service level this value is *M*.

Minimize cost:

$$Min \sum_{t=1}^{T} \sum_{c=c}^{C} \sum_{e=e}^{E} \begin{pmatrix} (hds_t + hda_t) * CDS + hns_t * CNS + CSA * hsa_t + CSU * hsu_t + CHO * hho_t + \\ (hexd_t - hds_t) * CEXD + (hexa_t - hda_t) * CEXD + (hexn_t - hdn_t) * CEXN - \\ (hda_t - hld_t) * CDS - (hda_t - hla_t) * CDS - (hns_t - hln_t) * CNS + \\ mr_{c,t} * CPU_c + ie_{e,t}^{int,+} * CI_e^{int,+} + ie_{e,t}^{ext,+} * CI_e^{ext} + \\ ic_{c,t}^{int} * CI_c^{int} + ic_{c,t}^{ext} * CI_c^{ext} + ic_{c,t}^{dock} * CI_c^{dock} + CLS * (ie_{e,t}^{int,-} - ie_{e,t}^{ext,-})^+ \end{pmatrix} \tag{3}$$

Maximize service level:

$$Min \sum_{t=1}^{T} \sum_{c=c}^{C} \sum_{e=e}^{E} \begin{pmatrix} (hds_t + hda_t) * CDS + hns_t * CNS + CSA * hsa_t + CSU * hsu_t + CHO * hho_t + \\ (hexd_t - hds_t) * CEXD + (hexa_t - hda_t) * CEXD + (hexn_t - hdn_t) * CEXN - \\ (hda_t - hld_t) * CDS - (hda_t - hla_t) * CDS - (hns_t - hln_t) * CNS + \\ mr_{c,t} * CPU_c + ie_{e,t}^{int,+} * CI_e^{int,+} + ie_{e,t}^{ext,+} * CI_e^{ext} + \\ ic_{c,t}^{int} * CI_c^{int} + ic_{c,t}^{ext} * CI_c^{ext} + ic_{c,t}^{dock} * CI_c^{dock} + M * (ie_{e,t}^{int,-} - ie_{e,t}^{ext,-})^+ \end{pmatrix} \tag{4}$$

5.1.7 Constraints

State of inventory

The first constraint is designed to account for the fact that the inventory can be either positive or negative. This is done such that the cost in the objective function can be calculated. It should be noted that this only holds for the inventory for end-products as a there are no specific costs for having backlog for a specific component. When backlog for components occur, the end-product will also have backlog and therefore the cost of missing components is calculated indirectly through the lost sales.

$$ie^{int}_{e,t} = ie^{int,+}_{e,t} - ie^{int,-}_{e,t} \tag{5}$$
$$ie^{ext}_{e,t} = ie^{ext,+}_{e,t} - ie^{ext,-}_{e,t} \tag{6}$$

Conservation of flow (end-products)

The next constraint highlights the conservation of flow for end-products. This constraint states that the inventory level of end-products in month t is equal to the inventory level of end-products of the previous month plus the production in month t minus the net requirements of month t. Note here that the inventory can go below 0 as described in the previous constraint. Due to the fact that for t=1, $ie^{int}_{e,t-1}$ and $ie^{ext}_{e,t-1}$ are undefined, the constraint is split up. For t=1, $ie^{int}_{e,t-1}$ and $ie^{ext}_{e,t-1}$ are equal to SIE^{int}_e and SIE^{ext}_e or SB_e if there is negative starting inventory. This yields the following constraint:

For t = 1:

$$ie^{int}_{e,t} + ie^{ext}_{e,t} = SIE^{int}_e + SIE^{ext}_e - SB_e + p_{e,t} - NR_{e,t}, \qquad \forall e \in E$$

For t > 1:

$$ie^{int}_{e,t} + ie^{ext}_{e,t} = ie^{int}_{e,t-1} + ie^{ext}_{e,t-1} + p_{e,t} - NR_{e,t}, \qquad \forall e \in E \tag{7}$$

Conservation of inventory (components)

Similar to the previous constraint, this constraint is developed for the conservation of inventory for components. The same logic holds, where the inventory of components is equal to the inventory of the previous month but the purchased components in that month are added to the inventory. Finally, the quantity used for production in that month is subtracted. Similar to the previous constraint, the constraint is split up for t=1 and t≠1 to incorporate the starting inventory parameters.

For t = 1:

$$ic^{int}_{c,t} + ic^{ext}_{c,t} + ic^{dock}_{c,t} = SIC^{int}_c + SIC^{ext}_c + SIC^{dock}_c + mr_{c,t} - B_{c,e} * p_{e,t} \qquad \forall e \in E, c \in C$$

For t > 1:

$$ic^{int}_{c,t} + ic^{ext}_{c,t} + ic^{dock}_{c,t} = ic^{int}_{c,t-1} + ic^{ext}_{c,t-1} + ic^{dock}_{c,t-1} + mr_{c,t} - B_{c,e} * p_{e,t} \qquad \forall e \in E, t \in T, c \in C \tag{8}$$

Upper and lower bounds - Material

This constraint ensures that the amount of component c bought in period t falls between the minimum and maximum order quantities.

$$E_{c,t}^{min} \leq mr_{c,t} \leq E_{c,t}^{max} \qquad \forall c \in C, t \in T \tag{9}$$

Inventory boundaries

The following constraints deal with the maximum quantity which can be stored at the aforementioned storage environments during month t of the end-products and components, respectively.

$$\begin{aligned}
ie_{c,t}^{int} &\leq SE_{c}^{intmax} \qquad \forall c \in C, t \in T \\
ie_{c,t}^{ext} &\leq SE_{c}^{extmax} \qquad \forall c \in C, t \in T \\
ic_{c,t}^{int} &\leq SC_{c}^{intmax} \qquad \forall c \in C, t \in T \\
ic_{c,t}^{ext} &\leq SC_{c}^{extmax} \qquad \forall c \in C, t \in T \\
ic_{c,t}^{dock} &\leq SC_{c}^{dockmax} \qquad \forall c \in C, t \in T
\end{aligned} \tag{10}$$

Upper bounds production - Material

Similar to machine, production in month t can only take place if sufficient components are available.

$$\sum_{e=e}^{E} p_{e,t} * B_{c,e} \leq ic_{c,t}^{int} + ic_{c,t}^{ext} + ic_{c,t}^{dock} + mr_{c,t} \qquad \forall t \in T, c \in C \tag{11}$$

Upper bounds production - Machine

The following constraint highlights the maximum number of end-products which can be produced in month t based on the maximum machine capacity.

$$\sum_{e=e}^{E} \frac{p_{e,t}}{R_e} \leq HM_{t}^{max} \qquad \forall t \in T \tag{12}$$

Upper bounds production - Labour

With respect to labour, the following constraint ensures that the total hours used for the production of every end-product is equal to the total hours of different shifts available in that month.

$$\sum_{e=e}^{E} \frac{p_{e,t}}{K_e} = hds_t + hda_t + hns_t + hsa_t + hsu_t + hho_t + hexd_t + hexn_t \qquad \forall t \in T \tag{13}$$

Sufficient labour

This constraint ensures that there are enough workers to run the production line for each end-product e in each period t.

$$1 \leq TS_e \leq W_t + exp_t \qquad \forall e \in E, t \in T \tag{14}$$

Upper bound borrowed workers

This constraint complements the previous constraint as the amount of borrowed workers cannot exceed the maximum number of available workers in each period.

$$0 \leq exp_t \leq EXP_t^{max} \qquad \forall t \in T \tag{15}$$

Upper and lower bounds labour

The following constraint ensures that the labour hours in month t do not fall below or go above the capacity corridor.

$$L_t^{min} \leq hds_t + hda_t + hns_t + hsa_t + hsu_t + hho_t + hexd_t + hexn_t + hld_t + hln_t + hi_t \leq L_t^{max} \qquad \forall t \in T \tag{16}$$

Capacity labour - types of shifts

The following constraints ensure that, for every type previously defined shift, the hours assigned to that type does not exceed the total available hours per shift type for month t.

$$\begin{aligned} hds_t &\leq wD * AD_t && \forall t \in T \\ hda_t &\leq wA * AD_t && \forall t \in T \\ hns_t &\leq wN * AD_t && \forall t \in T \\ hsa_t &\leq wSA * ASA_t && \forall t \in T \\ hsu_t &\leq wSU * ASU_t && \forall t \in T \\ hho_t &\leq wHO * AHO_t && \forall t \in T \end{aligned} \tag{17}$$

Extending shifts

The following constraints highlight the opportunities regarding extending shifts for regular (day, afternoon, night) days. The constraint showcase that one can only introduce shift extensions if the regular shifts hours are not sufficient. However, the shift extensions are constrained by the maximum number of hours available per month t.

$$\begin{aligned} WD * AD_t \leq hexd_t &\leq WD * AD_t + HEXD_t^{max} && \forall t \in T \\ WA * AD_t \leq hexa_t &\leq WA * AD_t + HEXA_t^{max} && \forall t \in T \\ WN * AD_t \leq hexn_t &\leq WN * AD_t + HEXN_t^{max} && \forall t \in T \end{aligned} \tag{18}$$

Reducing shifts

With regards to reducing shifts, the same logic holds as for extending shifts. However, in this case, one can only reduce the shift hours when the assigned hours are smaller than the available hours. Once again, this can only be done to a certain extent and is limited by the maximum number of hours per month t a shift can be reduced with.

$$\begin{aligned} WD * AD_t - HLD_t^{max} \leq HLD_t \leq WD * AD_t \qquad \forall t \in T \\ WA * AD_t - HLA_t^{max} \leq HLA_t \leq WA * AD_t \qquad \forall t \in T \\ WN * AD_t - HLN_t^{max} \leq HLN_t \leq WN * AD_t \qquad \forall t \in T \end{aligned} \tag{19}$$

Non-negativity constraint

Finally, all decision variables should be equal or larger than 0.

$$\begin{aligned} exp_t, hi_t, hds_t, hda_t, hns_t, hsa_t, hsu_t, hho_t, hexd_t, hexa_t, hexn_t, \\ hld_t, hla_t, hln_t, mr_{e,t}, ie_{e,t}^{int}, ie_{e,t}^{ext}, ic_{c,t}^{int}, ic_{c,t}^{ext}, ic_{c,t}^{dock}, p_{e,t} \geq 0 \end{aligned} \tag{20}$$

Integers

Due to the nature of the problem, the decision variables can only be integers. This will be explicitly accounted for in the model. It should be noted that the inventory decision variables do not have to be integers. This is due to the fact that the starting inventory is an integer and the order quantity and production in every period are also integers. For this reason, the inventory level in each period is implicitly already an integer.

$$exp_t, hi_t, hds_t, hda_t, hns_t, hsa_t, hsu_t, hho_t, hexd_t, hexa_t, hexn_t, hld_t, hla_t \text{ are integer} \tag{21}$$

5.1.8 Assumptions

To finalize this section, the assumptions which are relevant to this model are discussed. These assumptions serve as a basis to further extend the model where possible and relevant. The assumptions made for the model can be divided into two categories. The first category concerns the practicality of the model. After all, the ultimate purpose is to convert this model in a practical, user-friendly tool. Introducing a significant number of decision variables and parameters might render the model too complex to use in practice. The second category concerns the level of decision-making. The model should account for information and decisions which are relevant for the CP to consider. Therefore, information and decisions upon which a CP cannot act should therefore be omitted in the model. The following assumptions are considered:

Practicality

- Labour force is not shared. The current model assumes that there is a set amount of workers available per production line. As a result, production can only occur if there are sufficient workers available for each production line. The model does assume that a production line can borrow workers from another production line (exp_t) but does not consider the aggregate amount of workers available for all production lines.
- Idle time can only occur during regular day shifts. A vast majority of monthly labour hours are attributed to regular day shift hours. In months where production is lower than the labour

capacity, the idle time will therefore also occur in these shift hours. In months where labour capacity has to be increased to meet production hours, additional 'special' shifts can be allocated or regular shifts can be extended accordingly. Therefore, it is reasonable to assume that when additional 'special' shifts are assigned there will be limited to no idle time during these shifts.

- Unable to extend or reduce 'special' shifts. With regards to adjusting shift hours, the model currently assumes that adjustments can be made to only regular workday shifts. The same argument holds as the one mentioned at idle time as these 'special' shifts are only introduced when they are required and are thus fitted accordingly.
- Non-sharing of components. In the current model, each end-product in a production line has its own inventory of components. Therefore, the total demand for end-products (or subassemblies) which require the same components is not considered by the CP whilst making decisions. This assumption is in practice realistic and also non-problematic as long as there is sufficient stock for all end-products. After all, the inventory level and safety stock is determined on the aggregate demand of components. This only becomes an issue when there are not enough components to cover all altered requirements of end-products. In this case, the CP can manually intervene to adjust the maximum order quantity to account for a reduction of component availability. Since the lead time is assumed to be 0, which is discussed later, the maximum order quantity is equal to the maximum component availability in that period.
- No transshipments of material between warehouses. The current model is developed in such a way that each component and end-product has its own storage facility on local (plant) level. In reality, the same components are kept in multiple different warehouses across the world. Theoretically, if one plant runs out of stock for a specific component, the CP can order it from a different warehouse assuming it has sufficient stock. In practice, this does not occur often as the cost of transshipping these components would be very high. Furthermore, this option does not occur often as component availability is often not a local issue which means that if one plant lacks a specific component, other plants will likely have the same issue. It is for these reasons that the model considers local stock as the only available stock for production and thus it is assumed that transshipment of material is not possible.
- No airfreight. In reality, the CPs can consider airfreighting the end-products. Airfreighting end-products results in an increased cost of transportation but reduces the lead time of transportation. As a result, a part of the lost sales can be recovered as the end-products arrive earlier than the usual means of transport. Due to the complexity that this option brings by introducing different (region-specific) lead times and costs, this option is for now considered to be unavailable.
- One supplier per component. The current model implicitly assumes that a component can only be bought at one supplier as there is one set price for a specific component. In reality, this is also often the case as most components are Hilti specific. This can be deduced via the BoM as a relatively small number of components in a BoM can be bought at more than one supplier. It is therefore reasonable to assume that there is only one supplier per component.
- Fixed purchasing price. In the current model, the parameter which indicates the purchasing price is not dependent on the month t. This is a reasonable assumption to make since at the time of decision-making, the purchasing price of a component is fixed. For accuracy reasons, this purchasing price should be updated every time the model is ran.
- Machine operator. The model implicitly assumes that, when a team is assigned to a production line, there is at least one person in that team that can operate the machine. This also implies that the machine is relatively simple to operate and therefore does not require a specialist. The

latter can be the case for some production lines and adjustments in the base model can be made to account for these instances. For now, this will be omitted from the generic model.

- Constant labour productivity. The current model does not differentiate between different levels of productivity for different shifts. One can for example argue that the productivity of the workers could be lower for 'special' shifts due to lower motivation. If there are significant differences between productivity levels for shifts, the CP can opt to adjust the expected output by applying a multiplicative factor to account for the qualitative aspects.
- There is one team assigned to one shift. This implies that the output per end-product e is constant per shift hour and thus cannot be increased by adding an additional team to a shift. For machine-driven plants, this assumption is reasonable as additional workers would not increase productivity. For labour-driven plants, this assumption might not hold as adding additional workers increases productivity. The main problem here is that adding one additional team to a production line does not result in a linear increase in production output due to, for example, overcrowding the production line. One can incorporate this complexity in the model by, for instance, assigning different output levels for different team sizes. For now, this is omitted from the model.
- Sales quantity is equal to the net requirements. As previously explained, the CPs receive the net requirements as input for their decision-making which are based on the expected sales. These net requirements are then further altered to incorporate the current backlog or inventory which is described as the altered requirements. The altered net requirements influence the required production quantity whilst the net requirements are still directly linked to the expected sales. Since it is always optimal to sell the same quantity of end-product as the net requirements of the period, this is a reasonable assumption to make. If a CP expect a higher or lower sales quantity than forecasted, they can manually adjust the net requirements accordingly.
- Backlog can be recovered in subsequent periods. When the net requirements cannot be met due to lack of production capacity, it is assumed that backlog is created. Therefore, it is assumed that (eventually) the net requirements can be (at least partially) fulfilled resulting in limited lost demand. The parameter 'cost of lost sales' should therefore be interpreted as a penalty cost for not being able to meet demand in a period. An alternative way of describing this cost is the cost of production backlog which can also be described as the cost of not being able to sell.
- Decision variables are integers.

Decision level

- Constant storage capacities. In the current model, the storage capacity for each storage facility is constant over time. In practice, the storage capacity can either decrease or increase depending on the utilization. However, this is not a decision that is or should be made by the CP. This decision is either an operational (plant level) decision or a strategic decision if significant expansions are considered. Therefore, changes in storage capacities over time is omitted from the model.
- Components have zero lead-time. In the current model, it is assumed that components purchased at time t are also available for production at time t. It goes without saying that this is an unreasonable assumption to make in practice as components always have a lead time larger than zero. However, taking into consideration the perspective of the CP and the context of this project, it is important to know how much material is required (and available) for production at a certain month. Given this quantity, the moment when an order should be placed can be calculated by taking into account the lead time. It is therefore relevant for the CP to know the quantities required at month t such that this information can conveyed to the material managers who can order at the appropriate moment in time.

- Component retrieval has zero lead time. Similar to the previous assumption, the model assumes that, the inventory in month t, irrespective of storage location, is available for production at month t. Whilst in reality there will be a lead time for retrieving a component from, for example, external storage, it is not in the CPs interest to account for this lead time. The CP will know how much material is needed and from which storage facility it should be extracted. This information can then be conveyed to the logistics department which can ensure that the components will arrive in time for production.
- No training for newly hired personnel. When new personnel is hired, they often require intensive training in order to be fit to operate a production line. This process, which can take from a few weeks to a few months, is important to account for from a plant's perspective but not from a CP perspective. For the CP, the information that is relevant is the workforce required to the altered requirements for every month in the planning horizon. Therefore, if a CP foresees a lack of labour capacity in the future, it is important to signal this information to the plants such that the hiring process can start at the appropriate time.
- Assumes no safety stock. The usage of safety stock can be a manual intervention from the CP when they deem it necessary to use. Incorporating safety stock into the model would mean that the model automatically use this safety stock if production does not meet the net requirements unless there is a cost of using the safety stock. To avoid this complexity, the integration of the safety stock into the model is omitted. For now, the CPs can still decide to use the safety stock after the model has calculated an optimal solution.

With all relevant information about the mathematical model presented, this section can be concluded. The following section will discuss the process of implementing this model in practice.

6 Model development

In this section, the development of the operational model will be discussed. The previous section highlighted the mathematical representation of the conceptual model. In order to make the model operational however, a bottom-up approached will be used. It was concluded that the mathematical model as presented in the previous section is too complex to be implemented as is. For this reason, it is opted to simplify the model in order to make it accessible for end-user interaction in the form of a tool. After that, the tool will be tested by allowing a variety of CPs to interact with the tool. Based on the feedback provided by the CPs, the tool will be modified. This will be done according to a priority list which is derived from the feedback of the CPs. It should be noted that this will be an iterative process; after each modification the model is tested again and further feedback is collected from the CPs. When the right balance between accuracy and complexity is found, the development of the model will be concluded.

6.1 Practical model

The starting point of the practical model is the mathematical model developed in the previous section. However, the following assumptions are added to reduce the complexity of the model:

- The day and afternoon shift will be aggregated to a regular day shift.
- The option to extend and reduce shifts will be omitted.
- The shift model is omitted.
- The integer requirement for the different types of shift hours are relaxed such that the model requires less computational power, making the model an MILP.
- The different types of storage facilities will be aggregated such that there is only one storage location. It is furthermore assumed that this storage location has infinite capacity.

These additional assumptions result in the parameters as displayed in table 8 and the decision variables as displayed in table 9.

Parameters		
Parameter	*Definition*	*Notation*
Workforce level	Number of workers in month t	W_t
Work hours per shift (regular)	The amount of work hours per shift (06:00-22:00)	WR
Work hours per shift (night)	The amount of work hours per shift (22:00-06:00)	WN
Work hours per shift (saturday)	The amount of work hours per shift (saturday)	WSA
Work hours per shift (sunday)	The amount of work hours per shift (sunday)	WSU
Work hours per shift (holiday)	The amount of work hours per shift (holiday)	WHO
Working days (regular)	The number of regular working days in month t	AD_t
Working days (Saturday)	The number of workable Saturdays in month t	ASA_t
Working days (Sunday)	The number of workable Sundays in month t	ASU_t
Working days (Holiday)	The number of workable Holidays in month t	AHO_t
Regular shift cost	Cost of regular labour hours (08:00-00:00)	CDS
Night shift cost	Cost of night labour hours (00:00-08:00)	CNS
Saturday shift cost	Cost of Saturday labour hours	CSA
Sunday shift cost	Cost of Sunday labour hours	CSU
Holiday shift cost	Cost of labour hours on holiday days	CHO
Maximum labour hours	The maximum number of labour hours in month t	L_t^{max}
Minimum labour hours	The minimum number of labour hours in month t	L_t^{min}
Conversion factor	Amount of end-product e made per shift hour	K_e
Team size	The amount of people required to run the production line for end-product e	TS_e
Maximum number of borrowed workers	The maximum number of additional workers available in month t	EXP_t^{max}
Component cost	Purchasing price of component c	CPU_c
Cost of lost sales (regular)	Cost of 1 unit e of unfulfilled demand	CLS_e
Cost of lost sales (Maximize service level)	Cost of 1 unit e of unfulfilled demand (Max service level)	M_e
Cost of end-product inventory	Cost of keeping 1 unit of end-product e inventory	CI_e
Cost of component inventory	Cost of keeping 1 unit of component c	CI_c
Minimum order quantity	Minimum order quantity of component c in period t	$E_{c,t}^{min}$
Maximum order quantity	Maximum order quantity of component c in period t	$E_{c,t}^{max}$
Starting end-product inventory	The amount of end-product e in storage at time t=0	SIE_e
Starting end-product backlog	The amount of end-product e in backlog at time t=0	SB_e
Starting component inventory	The amount of component c in storage at time t=0	SIC_c
Production coefficient	Number of component c required for production of 1 unit of end-product e	$B_{c,e}$
Throughput	Number of end-product e which can be produced by a machine per hour	R_e
Maximum machine capacity	Maximum hours in month t a machine can produce	HM_t^{max}
Net requirements	The net requirements of end-product e in period t	$NR_{e,t}$

Table 8: Parameters of the generic model

Decision variables		
Decision variable	*Definition*	*Notation*
Additional workers	Number of workers borrowed from a different production line in month t	exp_t
Workday hours assigned (regular)	Hours assigned to morning shifts in month t (06:00-22:00)	hdr_t
Workday hours assigned (night)	Hours assigned to night day shifts in month t (22:00-06:00)	hns_t
Saturday hours	Hours assigned to Saturday shifts in month t	hsa_t
Sunday hours	Hours assigned to Sunday shifts in month t	hsu_t
Holiday hours	Hours assigned to holiday shifts in month t	hho_t
Material requirement	Amount of component c bought at time t	$mr_{c,t}$
Inventory end-product	Amount of end-product e stored at time t	$ie_{e,t}$
Inventory end-product	Amount of end-product e stored at time t (positive)	${ie^+}_{e,t}$
Inventory end-product	Amount of end-product e stored at time t (negative)	${ie^-}_{e,t}$
Inventory component	Amount of component c stored internally at time t	$ic_{c,t}$
Production quantity	Amount of end-product e produced at time t	$p_{e,t}$

Table 9: Decision variables of the generic model

The objective function of the model is the following (minimize cost):

$$Min \sum_{t=1}^{T} \sum_{c=c}^{C} \sum_{e=e}^{E} \Big(hdr_t * CDS + hns_t * CNS + CSA * hsa_t + CSU * hsu_t + CHO * hho_t \\ + CHI * hi_t + mr_{c,t} * CPU_c + ie^{+}_{e,t} * CI_e + ic_{c,t} * CI_c + CLS_e * ie^{-}_{e,t} \Big) \tag{22}$$

To maximimize the service level, the following objective function can be used:

$$Min \sum_{t=1}^{T} \sum_{c=c}^{C} \sum_{e=e}^{E} \Big(hdr_t * CDS + hns_t * CNS + CSA * hsa_t + CSU * hsu_t + CHO * hho_t \\ + CHI * hi_t + mr_{c,t} * CPU_c + ie^{+}_{e,t} * CI_e + ic_{c,t} * CI_c + M_e * ie^{-}_{e,t} \Big) \tag{23}$$

The model is subject to the following constraints:

State of inventory

$$ie_{e,t} = ie^{+}_{e,t} - ie^{-}_{e,t} \qquad \forall e \in E, t \in T \tag{24}$$

Conservation of flow (end-products)

For t = 1:

$$ie_{e,t} = SIE_e - SB_e + p_{e,t} - NR_{e,t} \qquad \forall e \in E$$

For t > 1:

$$ie_{e,t} = ie_{e,t-1} + p_{e,t} - NR_{e,t} \qquad \forall e \in E \tag{25}$$

Conservation of inventory (components)

For t = 1:

$$ic_{c,t} = SIC_e + mr_{c,t} - B_{c,e} * p_{e,t} \qquad \forall e \in E, c \in C$$

For t > 1:

$$ic_{c,t} = ic_{c,t-1} + mr_{c,t} - B_{c,e} * p_{e,t} \qquad \forall e \in E, c \in C \tag{26}$$

Upper and lower bounds - Material

$$E^{min}_{c,t} \leq mr_{c,t} \leq E^{max}_{c,t} \qquad \forall c \in C, t \in T \tag{27}$$

Upper bounds production - Machine

$$\sum_{e=e}^{E} \frac{p_{e,t}}{R_e} \leq HM^{max}_t \qquad \forall t \in T \tag{28}$$

Upper bounds production - Material

$$\sum_{e=e}^{E} p_{e,t} * B_{c,e} \leq ic_{c,t} + mr_{c,t} \qquad \forall e \in E, t \in T, c \in C \tag{29}$$

Sufficient labour

$$1 \leq TS_e \leq W_t + exp_t \qquad \forall e \in E, t \in T \tag{30}$$

Upper bound borrowed workers

$$0 \leq exp_t \leq EXP_t^{max} \qquad \forall t \in T \tag{31}$$

Upper bounds production - Labour

$$\sum_{e=e}^{E} \frac{p_{e,t}}{K_e} = hdr_t + hns_t + hsa_t + hsu_t + hho_t \qquad \forall t \in T \tag{32}$$

Upper and lower bounds labour

$$L_t^{min} \leq hdr_t + hns_t + hsa_t + hsu_t + hho_t + hi_t \leq L_t^{max} \qquad \forall t \in T \tag{33}$$

Capacity labour - types of shifts

$$\begin{aligned} hdr_t &\leq WD * AD_t && \forall t \in T \\ hns_t &\leq WN * AD_t && \forall t \in T \\ hsa_t &\leq WSA * ASA_t && \forall t \in T \\ hsu_t &\leq WSU * ASU_t && \forall t \in T \\ hho_t &\leq WHO * AHO_t && \forall t \in T \end{aligned} \tag{34}$$

Non-negativity constraint

$$hdr_t, hns_t, hsa_t, hsu_t, hho_t, hi_t, exp_t, mr_{c,t}, p_{e,t}, ie^+_{e,t}, ie^-_{e,t} \geq 0 \tag{35}$$

Integers

$$exp_t, mr_{c,t}, p_{e,t} \text{ are integer} \tag{36}$$

6.2 Implementation

With the mathematical model being defined, the next step is to select an environment in which the mathematical model can be programmed and executed. The main requirements of such an environment are the following:

- Ability to implement and execute LPs.
- User-friendly environment or ability to work with user-friendly environments.

Based on these requirements, it was decided to implement and execute the model in Python. Python has a variety of packages available which supports the development and execution of LPs. For this project, it is decided to use the PuLP package. This package is equipped with the basic requirements of formulating an LP in an intuitive manner. Furthermore, the package comes with a standard solver called the Coin-or Branch and Cut solver which uses the simplex method at its foundation. However, the end-user is free to use a variety of third-party solvers. The advantage of the standard solver is that it requires no commercial license to use it. This comes at the cost of not being as powerful as commercially available solvers. For this project, the Gurobi solver was available which is a commercial solver. The Gurobi is significantly more powerful than the standard PuLP solver and therefore the Gurobi solver is used for this project. The second requirement is based on the accessibility of the model and its operation, especially with respect to the business environment. After all, there should be limited to no pre-knowledge required to operate the model. Whilst Python is not the most user-friendly environment, because it requires a certain degree of pre-knowledge, it does allow for flexibility as it has many ways of interfacing with external programs and applications. Therefore, whilst the programming part can be within the Python environment, the actual end-user interface can be developed externally. For this reason, Python is still considered to be suitable for this project provided that the end-user does not have to interact in the Python environment.

6.2.1 Verification and validation

In order to support the model and the results it produces, it is important to closely examine the output given the input parameters. This is especially relevant due to the complexity of the data and the underlying interdependencies which makes it difficult for end-user to assess the data. Since the end-user relies on the output to ultimately decide on the production plan for future periods, it is of utmost importance that the model does in fact provide the optimal solution for each given input. In other words, it is important to verify the model. Essentially, a model is verified when there are no errors in the programming code (Kleijnen, 1995). The author provides several ways of verifying a model depending on its nature. In this context, the model will be verified by 1) checking intermediate output, 2) checking the output of the complete model to different ways of solving the same scenario and 3) sensitivity analysis. After, or in parallel with, this verification process it is important to validate the model. Whereas verification is concerned about the debugging the model, the validation process is concerned about capturing the process under consideration in an accurate fashion in the model (Balci, 1994). According to Landry, Malouin, and Oral (1983), there are four different types of validation: conceptual, logical, experimental and operational validation. In this context, logical validation, which assesses the fit between conceptual and mathematical model, and operational validation, which assesses the fit between model output and actionability of the output, are primarily discussed. The author furthermore discusses multiple validation techniques which can be used according to the nature of the model. The most appropriate technique in this context is through 'face validation' which involves gathering knowledgeable people, in this case CPs and other stakeholders, to assess the validity of the model based on their expert opinion. Other techniques which further add to the validity of the model, such as sensitivity analysis, are considered as a part of the verification process (Sargent, 2010).

Verification

The verification steps consist of determining whether the output of the model is correct. In this context, the output can be deemed correct if in fact the minimum costs are found given the input parameters. Due to the complexity of the model and the underlying interdependencies between parameters, the model is first tested in a step-wise manner. For an LP, the best approach to do this is to relax all constraints and test them individually. Before doing so, the constraints were grouped together based on their relationship with other constraints and parameters. For instance, all constraints related to the resource machine were grouped together. Once all constraints were tested individually with their respective output verified, an additional constraint was added. This process continued until all groups of constraints were checked and the output verified. After that, groups of constraints were consecutively added to the model until all constraints were present. With all the individual constraints and groups of constraints accounted for, the next step was to check the output of the complete model. The output was verified in two-ways. First, the same model was ran in Python with a different solver. As stated earlier, the PuLP package include a standard solver. The output of the standard solver was compared to the Gurobi solver and both had the same results. Furthermore, the results were checked by manually performing the calculations to arrive at the total costs which yielded the same conclusion. Finally, the complete model is checked by using sensitivity analysis. Essentially, the input parameters are changed in such a way that the outcome is predictable. This is done with all parameter values. For example, the cost of lost sales of an end-product was set to one million. In this instance, the model should avoid loss of sales of this specific end-product at all costs as long as production capacity is available. With these tests performed, the verification step can be concluded.

Validation

Similar to verification, the steps taken in order to validate the model can also be seen as a process. Unlike the verification process, the validation process is not sequential but continuous as every step the project has to be validated. The method of validation throughout this process has been face validation. In other words, the fit of the model with reality is assessed by the experts. From the start of the project, there have been weekly meetings with the project's owners. In every meeting, the progress of the project was discussed and steered accordingly. With regards to conceptual validation, several individual meetings with stakeholders were held. These meetings lead to different perspectives on how they experienced their environment. For example, initially the model included the possibility of buying additional material on the spot market. After multiple discussions with different representatives of material, it became evident that this option could in fact not be exercised in practice. This led to revision of the conceptual model to ensure an accurate fit of reality. The information gathered from the different stakeholders was then combined and lead to the conceptual model which was presented again to the relevant stakeholders for approval. With the approval of the conceptual model, a suitable mathematical model could be developed. Essentially, the mathematical model translates all the actions and parameters which were mentioned in the conceptual model in a formal way without omitting any relevant actions or parameters. This translation could be easily made due to the fact that the basis of the mathematical model is an LP. Due to the nature of the decision variables, it was chosen to account for the fact that they are integer and thus the LP is converted to an ILP. Furthermore, the fact that an ILP was used is also supported by literature based on vast amount of LPs for capacity planning models. The choice of an ILP further supports the aforementioned operational validity which specifically relates to the actionability of the output. One key consideration in selecting the model was the nature of the model. Due to the prominent role of uncertainty in the context of capacity planning, the selected model had to be able to account for that. There was therefore a choice between integrating the uncertainty in the form of variability in the model, thus making the model stochastic, or making the model deterministic and manually accounting for uncertainty. The latter was chosen as it fits better within the scenario analysis context. After all, the CP wants consistent results when they test their scenarios. Furthermore, the deterministic nature makes the model more transparent which is beneficial for the CP as it allows the CP to better develop and test their intuition. Moreover, the integration of the model into Excel, which will be discussed in further detailed in the next section, increases the practical usefulness of the model. It is therefore concluded that the model is operationally valid.

With both the validation and verification discussed, the model can be integrated into a different environment. Even though this subsection is concluded, the process of validating and verifying is not concluded. Every adjustment to the model follows the same steps as described in this section. The process of validating and verifying the model is only truly completed when the final adjustments have been made.

6.3 Integration

For the integration part of this model, the main goal is to make it more accessible and user-friendly. After all, one of the key requirements is that the model would be practical and easy to use. In current environment, this is not the case as discussed in section 6.2. With regards to creating this user-friendly environment there are two main options. First, a custom-made graphical user interface (GUI) can be developed. This can be done using several packages that installed within the Python environment. As an illustration, a package which is commonly used for such interfaces is Tkinter. Essentially, this package creates a separate window which can be customized to fit desired features, such as buttons and sliders, and links this to the Python data. This means that one can also execute Python code within this window if one makes a link accordingly. As a result, the end-user does not need to enter the Python environment which was one of the main requirements for operating the model in an user-friendly way. However, there are two drawbacks of using this package. First, every interaction with their respective display has to be developed from scratch. There is no preset interface or function which means development of the GUI will be a time-expensive effort. Second, there are limited options to import data from other sources than Python. This means that all data which is relevant for the model should be present and extracted from Python. Since the relevant data is stored in the ERP system, which cannot be accessed directly through Python, the Python environment would still need to be used to input and adjust the relevant data. For these two reasons, the second option under consideration was selected which was Excel. Excel alleviates the first mentioned issue because it already inherently has basic design features for a GUI. With regards to the second issue, Excel is very wide-used and dynamic. For this reason, most ERP systems have a way of outputting the relevant data in an Excel format. Furthermore, using Excel fits well with the current operations within Hilti as most data is stored and outputted in Excel. Additionally, Hilti makes use of PowerBI which uses Excel data as an input to analyse and visualize the data in a more structured way. It is therefore beneficial that the output of the model can also be linked to Excel to support further data analysis in the current systems. For these reasons, it is chosen to integrate the model using Excel.

6.3.1 Linking Python to Excel

After the environment is selected, the link from Python to Excel can be made. This is done using a package called OpenpyXL. This package allows for mutual interaction between Excel and Python. Therefore, data which is originally in the Python file can be exported to Excel and vice versa. With the introduction of Excel as primary data source, the functionality of Python is reduced to executing, and if necessary adjusting, the mathematical model. To make this transition, the way the data is structured in Excel should resemble the way the parameters are structured in Python. In Python, the data is structured within lists, nested lists, dictionaries and nested dictionaries. Data which is structured in lists are placed in separate Excel columns. The amount of data entries for each specific column is capped at the maximum limit of Excel which is 999999. For the other data structures, both rows and columns are used. For example, a dictionary requires a key and a corresponding value. In this case, the keys are listed in a separate column with their corresponding value in the next column. For nested dictionaries, a matrix has to be created. To illustrate, the net requirements of end-product e in period t is a nested dictionary. The combination of period t and end-product e would form the key which corresponds to a specific value. After transferring all the data to Excel, the model is tested and verified again using the same steps as described in section 6.2.1.

With the vast amount of data going into the model, it is important to structure the data into a practical and efficient manner. After all, the CP should be able to see and adjust all relevant data without having to access multiple sheets. In this context, the relevant data is the data that the CP uses to develop scenarios which is referred to as active data. The active data corresponds to all parameters values as defined by the mathematical model. To highlight that these values can be adjusted, the corresponding cells are marked green. On the other hand, there is also static data in the model. This is the data is imported from the ERP system but should not be adjusted by the CP. In this context, these are the BoMs, the production coefficients and the components and end-products which are produced on the production line. To ensure that these values will not be changed, the cells which contains this data is hidden. There are also edge cases which are the starting inventory of both end-products and components and the production speed for both labour and machine. Generally speaking, this is a number that should not be changed by the CP as it cannot be in influenced. However, in case of data inaccuracies or if the CP is curious, the CP might want to adjust these values. For this reason, they are still included in the main sheet but the cells containing the values are marked grey. The visual representation of this main datasheet can be found in Appendix A.

Whereas the datasheet functions as a database for Python to extract data from, the output of the model is not yet linked to Excel. In order to keep a good overview of the Excel file, an additional spreadsheet is created to output the results in. The results consist of all values of the decision variables, the total costs and the status of the optimization which can be either optimal or infeasible. It should be noted that there is a lot more information which can be deduced from these results. However, to keep the output concise, the most essential information is displayed. When the results are printed in the Excel sheet, they are automatically saved. Therefore, when a CP adjusts the parameter values in the data sheet and runs the model again, the results of this new scenario will be printed under the previous scenario. This allows the CP to easily compare and evaluate the scenarios. When the CP has completed their scenario analyses, they can simply delete all the data which is outputted in the results sheet.

In the current state, the data is retrieved and outputted in Excel. However, the actual execution of the program is still done within Python. This means that, even though the data is now accessible and adjustable in Excel, the CP would still have to enter the Python environment to run the model. As stated before, end-user interaction within the Python environment is undesirable as it requires a certain degree of pre-knowledge to navigate this environment which not all CPs have. To avoid the additional training and potential (inadvertent) breaking of the code by the CP, an executable file is created. Essentially, this file functions as the "run" button within Python. All the CP has to do is press this file and a command prompt will automatically run the code. When the code is done running, the output will be automatically appended to the results spreadsheet. During the solving time, the CP should not interact with the Excel sheet as this might corrupt the file. Therefore, Python is still required to run the model but it is not visible for the CP. With this final step completed, the model integration part is concluded.

6.4 Stakeholder feedback

The previous subsections have described the process of creating, implementing and integration the mathematical model. In the current stage, it can therefore be considered a proper decision-support tool. As the CP is the end-user of this tool, their feedback on the tool at this stage is crucial. Therefore, individual feedback sessions were scheduled to allow the CP to test the tool. Additionally, a preliminary presentation was given to gather additional feedback from the stakeholders. Based on the feedback, the following adjustments were made to the process and model:

- Filtering data input. From a data perspective, the concern was raised of too many data entries. In practice, the model can run any data set imported into Excel as long as it adheres to the maximum column and row length of Excel. However, it might be beneficial to apply a filter to reduce the data complexity. The main data source which could be filtered in this context is the BoM. As stated before, the model only accounts for the first level in the BoM. For some products, the BoM still contains a high number of components, even on the first level. For the CP, not all the components might be relevant for consideration. Components which, for instance, have not had a material issue in a year could be filtered out. This would automatically filter out the bulk stock, such as screws and bolts, which reduces the complexity of the model. The benefit is a more concise overview for the CP about the components which matter and an increased computational speed for the model. Currently, the ERP system can already distinguishes between bulk stock and non-bulk stock. Therefore, an additional step is added to the process which includes the screening and filtering of input data.

- BoM selection. This point relates to the fact that one end-product can have multiple BoMs. This could be the case with end-products with stand-alone components such as different batteries and/or adapters for instance. Due to the tactical position of the CP, the demand for each specific type of end-product is aggregated. It is therefore suggested to select one BoM which is representative of the end-product at its core and thus omit the stand-alone components.

- Costs disaggregation. Currently, the results of the model display the optimal production plan based on total minimum costs. It was chosen to only display the total costs to prematurely prevent information overload. As it turns out, the CPs wanted more insights into how these total costs are composed. For this reason, the total costs are disaggregated according to the feedback of the CP. Now, the total costs are shown per period and per relevant cost parameter. The cost parameter of both lost sales and shift hours are further disaggregated to show the individual end-product costs of lost sales and the costs per shift type.

- End of time horizon inventory. This suggestion was based on the option to include building inventory at the end of the preset time horizon of six months. There were two main arguments to support the introduction of this parameter. First, one might want to account for a potential increase in net requirements at the end of the time horizon. Since it is less expensive to store inventory compared to lost sales, it is beneficial to know how this increase can result in pre-production in coming periods. Additionally, one might want to consider using the safety stock within the six month period when the net requirements surpass production capability consistently. If the safety stock is issued, the CP can use this new parameter to build the inventory back up to the safety stock. Therefore, the parameter $DI_{e,t}$ was introduced. This results in a modification of constraint 25 where for t=6 holds:

$$ie_{e,t} = ie_{e,t-1} + p_{e,t} - NR_{e,t} + DI_{e,t}, \qquad \forall e \in E \tag{37}$$

- Miscellaneous costs. Currently, the costs which are included in the model are directly related to the decision variables. However, there are also costs which are specific to a situation which are therefore unaccounted for. It is therefore chosen to include an additional parameter to represent these costs: AC_t. This parameter can be used to represent any one-off costs which are specific to a scenario. For instance, if one were to pre-produce in a specific period, an additional forklift driver might be needed. With he introduction of this new parameter, this costs can be accounted for. Due to the fact that this cost does not affect any constraint and is therefore directly inserted into the objective function.

The final mathematical model, including the adjustments made after the feedback rounds, can be found in Appendix B. From the feedback rounds, it became evident that the CPs preferred practicality and transparency over adding complexity. Therefore, instead of adding additional constraints and parameters, such as the one described in section 5, changes were made accordingly. A final point of feedback was therefore also to develop a performance dashboard which provides visual insights into the results. This performance dashboard should also be able to expand upon the results, providing the CPs with more details about the specific scenarios they consider. Additionally, it benefits the CP during the pre-S&OP meetings as it helps the stakeholders understand the implications of the results in a more clear way.

6.5 Performance dashboard development

This section continues on the last section by highlighting how the performance dashboard is created. First, an additional sheet is created which duplicates the output of the model. This is done to prevent errors when deleting the output in the results sheet. After that, additional spreadsheets are created which can extract and visualize the relevant data from the duplicated sheet. It is chosen to create three duplicate dashboards. Therefore, the first three scenarios which are ran by the CP each have their own dashboard. It is chosen to have three duplicate dashboards as it is common practice to show three scenarios in the pre-S&OP meetings. However, additional dashboards can be created if that is deemed necessary.

As stated before, the goal of the dashboard is to visualize the results and provide additional information which cannot be directly extracted from the results. In doing so, it is also important to account for information the other stakeholders in the pre-S&OP meeting want to see. The following data is used as a starting point for the dashboard:

- Net requirements vs the production plan. Since the results only produce the production quantities per period, it is good to have an overview on how this relates to the net requirements. This information can also be found indirectly in the results since the results also contain the backlog and the inventory. However, having this information in one place is more convenient for the CP. This information is both displayed per specific time period and over time (cumulative).
- Cost distribution. This metric visualizes how the total cost are distributed amongst the different cost parameter per period. The visualization can help the CP to see the proportionality of the different cost parameters per period.
- Labour hours distribution. Similar to the cost distribution, the labour hours distribution highlights which shift type and how many hours per shift type is used per period.
- Component distribution. This graph provides insights into how the components are distributed to the end-products per period. Based on this information, the CP can see which products are prioritized by the model in case of component shortages. Additionally, it provides information about the production coefficient which could be helpful in complex cases.
- Components required vs their buy limits. The information in this graph showcases the maximum and minimum order quantity and the required per component per period. This information might be relevant for the material representatives and the CP in cases where there are structurally too few or too many components ordered.

- Inventory projections. Finally, the inventory and backlog for the end-products and the inventory of components are visualized which provides a more clear overview of the progression of this metric throughout the periods.

Figure 9 provides an impression of what the dashboard looks like. For the full dashboard with details, the reader is referred to Appendix C.

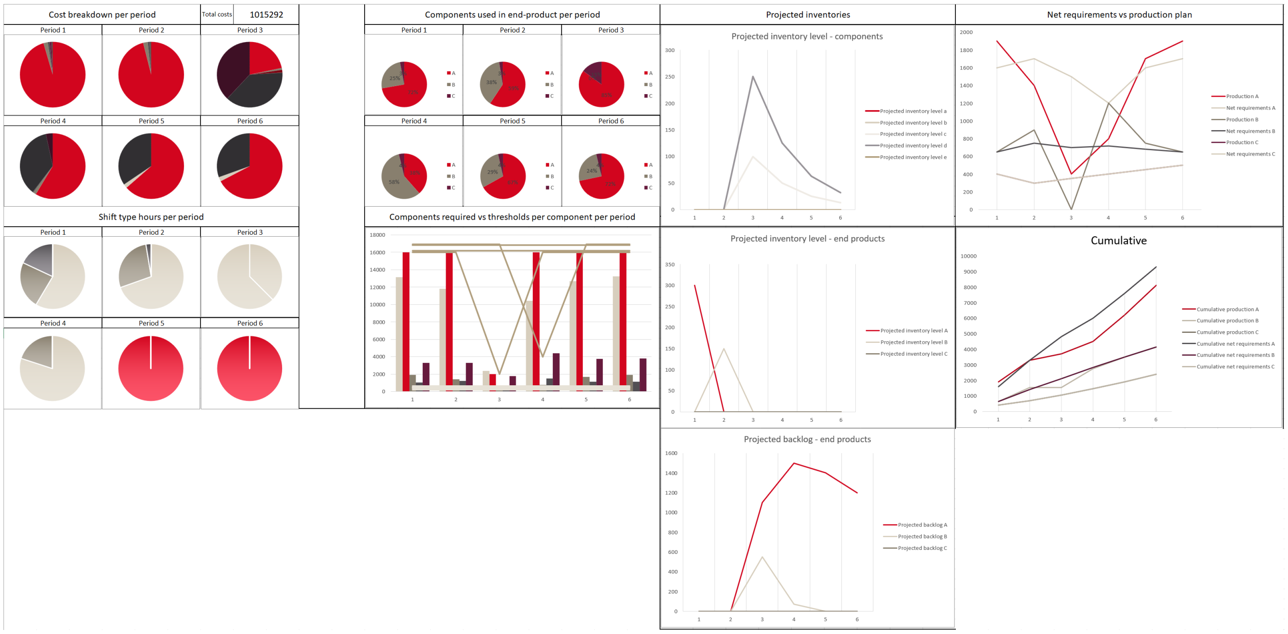

Figure 9: The initial performance dashboard

With the dashboard integration completed, the model development is concluded. Summing up, the starting point of the model was derived from the mathematical model. Due to the perceived complexity of the mathematical model, additional assumptions were made and constraints were relaxed. After that, the model was implemented in a Python environment. To ensure practicality and therefore end-user friendly interaction, the model was integrated into the Excel environment. Finally, the model was presented and scrutinized by stakeholders. The feedback from this presentation, together with the feedback gathered from individual meetings, were discussed and implemented. With every step taken into the development, the model was subjected to various verification and validation methods. A flowchart depicting the process described in this section is displayed in figure 10.

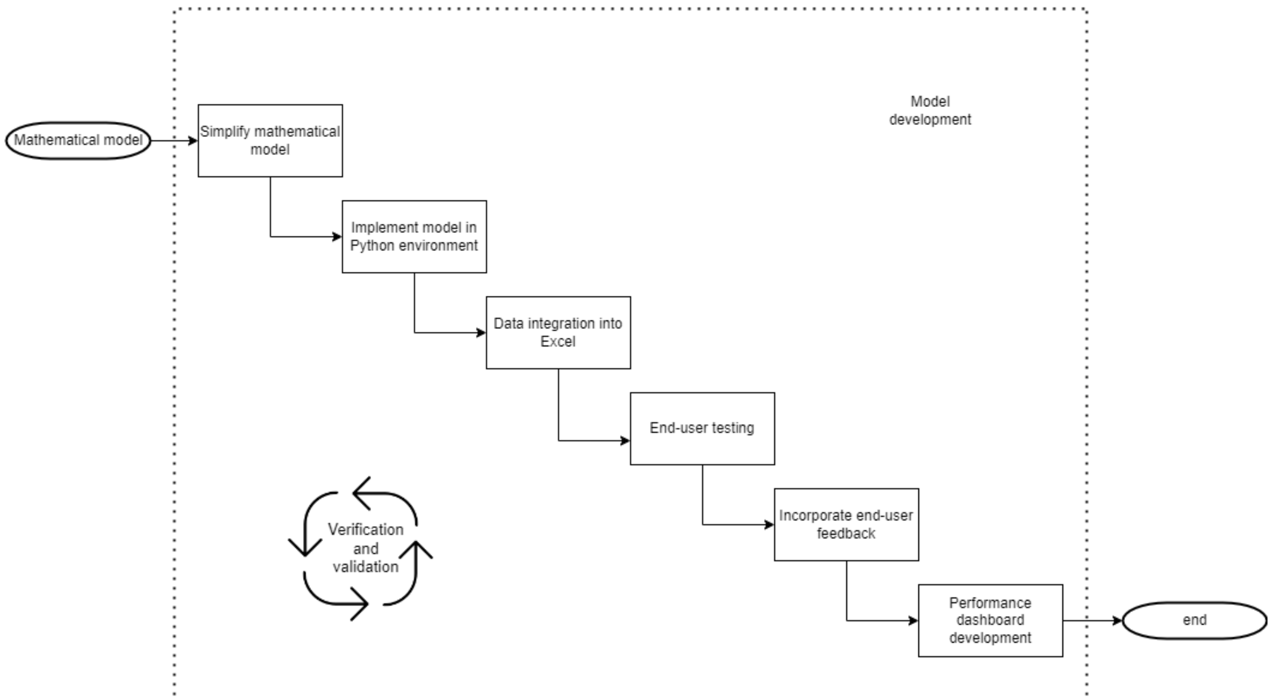

Figure 10: Flow chart of the model development process

7 Case study

This section is dedicated to testing the model by means of case studies. In doing so, it will become evident how to interpret the results and correctly draw conclusions. In this context, a case study is equivalent to a scenario. Three of the most common issues, as determined by the CPs and stakeholders present in the pre-S&OP, have been selected for this case study. The first scenario includes an acute component shortage. This will furthermore be compared to a known component issue to see how the results differ. The second scenario evaluates a significant reduction in labour hours available. The third scenario will investigate the impact of ordering a component which is uncertain to arrive with a short lead time. To test these case studies (scenarios), a hypothetical production line is created. This production line uses parameter values which are in close resemblance to several of Hilti's production lines. The advantage of using this hypothetical production line is that the data can be fully disclosed. This makes it suitable for repetition of this experiment by other researchers. Furthermore, one can still argue in favor of the model's validity as the only difference between an actual production line and the hypothetical production line are the parameter values. Essentially, a current production line could be the hypothetical production line when the values are slightly changed. For this reason, the hypothetical production line still serves its purpose for demonstrating the model. This production line has three end-products namely "A", "B" and "C". Furthermore, after the 'filtering process', five relevant components remain which are "a", "b", "c", "d" and "e". Before the scenarios are tested, a baseline performance is determined. This is the minimum costs based on the values of the decision variables when the production line faces no issues in either one or more of the critical resources. This way, the impact of an issue occurring can be properly assessed by comparing it to the costs of the baseline performance. The set of initial input parameters used to determine this baseline performance can be found in Appendix D. The resulting baseline performance can be seen in table 10. It should be noted here that, for conciseness sake, the cost parameters and decision variables with a value of 0 are not included in this table.

Total costs = 733650 CHF	**Periods**					
Costs (in CHF)	*1*	*2*	*3*	*4*	*5*	*6*
Total purchasing costs	117850	124450	115450	107200	121650	125350
Total day shift costs	3650	3750	3475	3120	3755	3950
Total costs	121500	128200	118925	110320	125405	129300
Decision variables						
Production "A"	1600	1700	1500	1200	1600	1700
Production "B"	650	750	700	720	680	650
Production "C"	400	300	350	400	450	500
Component "a" required	11650	12550	11350	10000	11850	12250
Component "b" required	14500	16000	14500	13200	14800	15000
Component "c" required	1600	1700	1500	1200	1600	1700
Component "d" required	1050	1050	1050	1120	1130	1150
Component "e" required	3300	3000	3150	3440	3610	3800
Day shift hours required	243,33	250	231,67	208	250,33	263,33

Table 10: Baseline performance of the hypothetical production line

7.1 Scenario 1: Decreased component availability

7.1.1 Unexpected shortage: No damage control

One of the most common issues which are discussed in pre-S&OP meetings are material shortages. Usually, these issues arise just before the pre-S&OP and impact the production capabilities immediately. To replicate this scenario, the maximum component availability for component "a" is cut to 10% of its initial value for the next period. Therefore, instead of having a maximum component availability of 16800 in period 1, it is now 1680. To see how this issue impacts the production capabilities, the model is executed. The results are displayed in table 11.

Total costs = 916053,80 CHF	**Periods**					
Costs (in CHF)	*1*	*2*	*3*	*4*	*5*	*6*
Total purchasing costs	53280	153448	148970	109252	121650	125350
Total day shift costs	856	4800	4800	3201	3755	3950
Total night shift costs	0	33,60	372	0	0	0
Total idle costs	2144	0	0	0	0	0
Total component inventory costs	655,20	237	0	0	0	0
Cost of lost sales "A"	80000	57200	2700	0	0	0
Cost of lost sales "B"	39400	0	0	0	0	0
Total costs	176335,20	215718,60	156842	112453	125405	129300
Decision variables						
Production "A"	0	2156	2590	1254	1600	1700
Production "B"	256	1144	700	720	680	650
Production "C"	400	300	350	400	450	500
Component "a" required	1680	16800	16800	10270	11850	12250
Component "b" required	12730	16000	16000	13470	14800	15000
Component "c" required	500	1656	2590	1254	1600	1700
Component "d" required	656	1444	1050	1120	1130	1150
Component "e" required	2512	3788	3150	3440	3610	3800
Day shift hours required	57,07	320	320	213,4	250,33	263,33
Night shift hours required	0	1,87	20,67	0	0	0
Idle time	142,93	0	0	0	0	0
Inventory "b"	10170	3950	0	0	0	0
Inventory "c"	500	0	0	0	0	0
Backlog "A"	1600	1144	54	0	0	0
Backlog "B"	394	0	0	0	0	0

Table 11: Model output for scenario 1

From the table, it becomes clear that an issue with this component severely impacts the production. This can partly be explained by the fact that this component is used in all the end-products of this production line which is information we can retrieve from the performance dashboard. Compared to the baseline performance, the total costs of this scenario have increased by almost 200.000 CHF. This can in a large part be attributed to the incurred cost of lost sales for end-product "A" and "B". This also reveals that, if there is an issue with component "a", the production of end-product "C" is prioritized. This in fact does not agrees with an initial intuition one might have as the cost of lost sales for end-product "B" is higher than end-product "C". A further investigation reveals that there are more components of "a" required for the production of end-product "B" compared to end-product "C" (figure 11). Therefore, even though the absolute cost of lost sales of "B" is higher, it is still relatively more cost effective to produce end-product "C" over end-product "B".

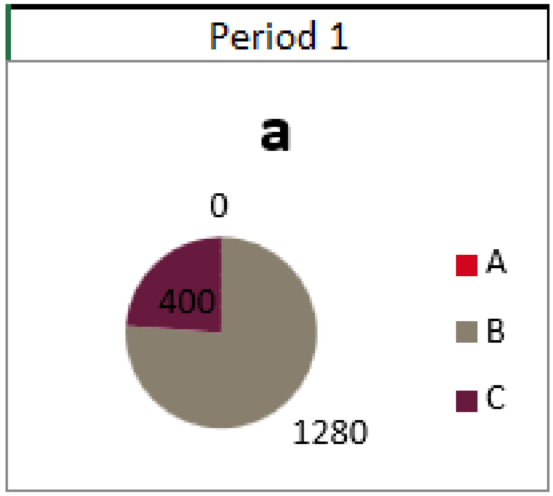

Figure 11: Scenario 1 - Component (a) allocation breakdown for period 1

Another interesting finding in this scenario is that inventory is being kept for components "b" and "c" in periods 1 and 2. Further analysis reveals that, for component "b", this is necessary to ensure that the higher production levels to overcome the backlog , can be assured. The fact that inventory has to be kept means that the, even if the maximum component quantity was ordered in the second period, this would not be enough to fulfill the production requirements of all products. This is further illustrated in figure 12). From this figure, it becomes evident that the required component amount of component "b" is equal to the maximum order quantity for two consecutive periods. Additionally, the order quantity is for all periods very close to the maximum order quantity. This insight might lead to a call for action for the materials managers as this maximum limit is resulting in an increased inventory cost for the first two periods. The graph furthermore explains that the reason why inventory is being kept for component "c" is due to the minimum order quantity.

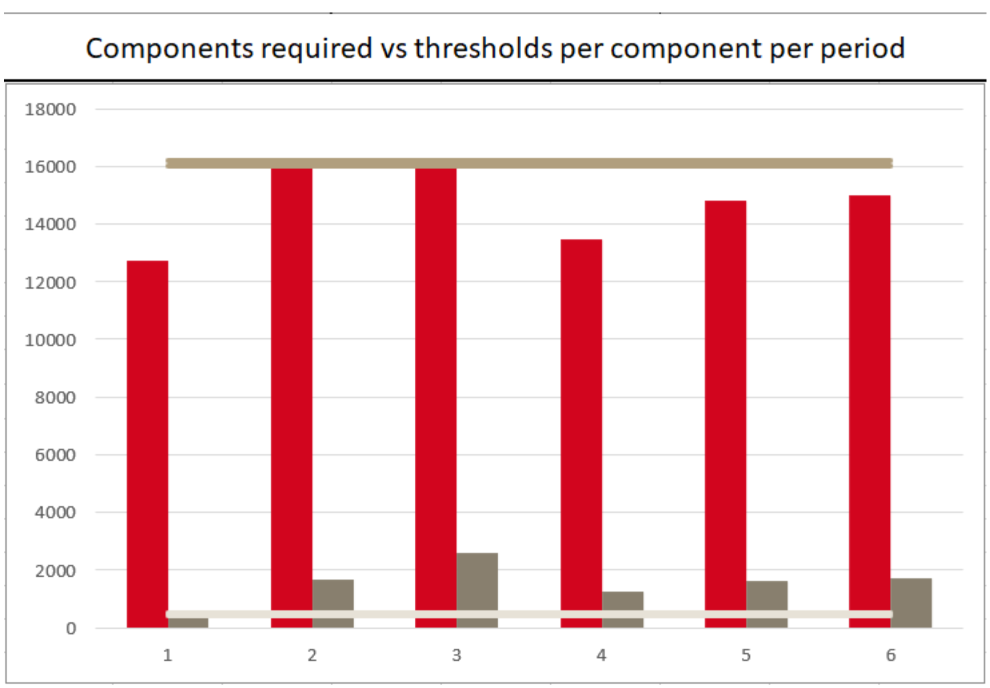

Figure 12: Scenario 1 - Component "b" (red) and component "c" (grey) required vs minimum and maximum order quantity per period (Unexpected shortage)

Finally, the component shortage also has impact on the other resources. For instance, with regards to the labour hours, there is a significantly amount of idle time. This is due to the fact that the workers have a minimum amount of working hours and therefore this idle time is. This would lead to a decrease of workers motivation as the workers will be assigned different, maybe less enjoyable work. Additionally the model indicates that 1,87 and 20,67 night shift hours are required in periods 2 and 3, respectively. These are low numbers but it at least indicates that the regular shift hours would not be sufficient for the production level required. The plant can easily solve this situation by a combination of overtime and an additional shift. This initial scenario can be concluded by visualizing the net requirements vs the production plan which can be found in figure 13.

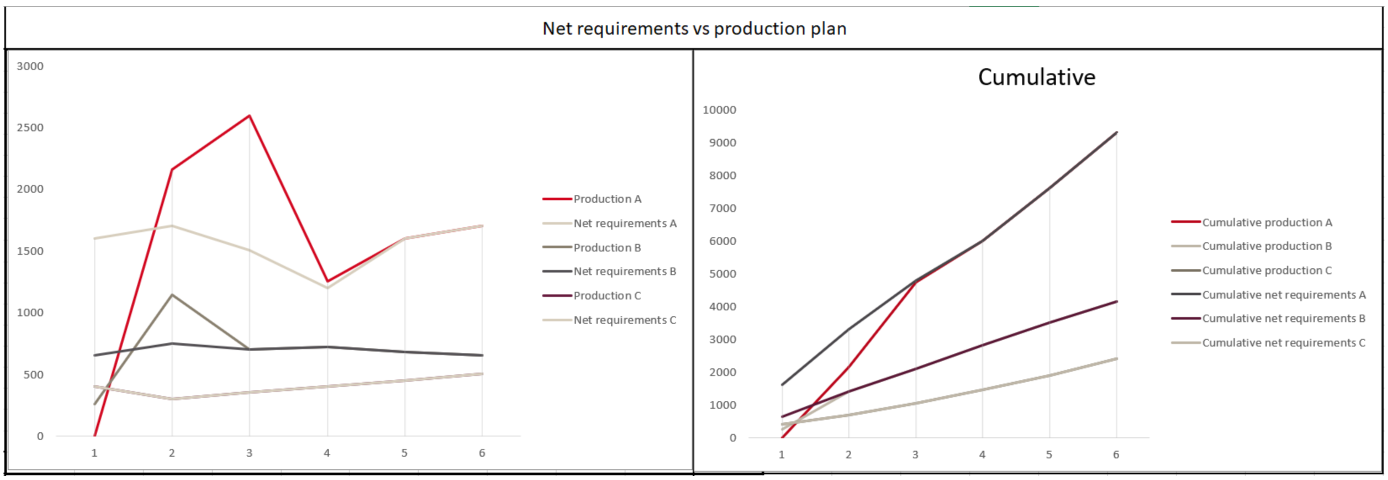

Figure 13: Scenario 1 - Net requirements vs production over time

7.1.2 Unexpected shortage - damage control

In the previous case, no action was taken to mitigate the impact of the component issue. However, in this scenario, the CP has one option to increase the amount of available end-products for this period by using the safety stock. To compare this scenario with the previous one, it is assumed that there is a safety stock which equals roughly 20% of the net requirements. This results in a safety stock of 300, 130 and 80 for end-product "A", "B" and "C", respectively. As a result, the net requirements for period 1 decrease by 300, 130 and 80 for end-product "A", "B" and "C", respectively. To account for the use of safety stock, the desired end inventory parameter is used to ensure that the safety stock is rebuild at the end of the time horizon. Additionally, a penalty cost of 10000 CHF is applied for using the safety stock. The results of this scenario can be found in table 12.

The results show that if the CP decides to use the safety stock, the total costs will decrease by roughly 40000 CHF. This scenario further indicates that the currently set maximum order quantity of component 'b' can be problematic as inventory has to be build up in periods 4 and 5 to ensure that the net requirements combined with the safety stock replenishment can be fulfilled. The analysis shows that the use of safety stock is favourable for this scenario as the production plan and the net requirements are more streamlined as can be seen in figure 14.

Total costs = 871378,30 CHF	Periods					
Costs (in CHF)	*1*	*2*	*3*	*4*	*5*	*6*
Total purchasing costs	46076	150870	137994	108400	124050	144560
Total day shift costs	752	4800	4522	3120	3755	4650
Total night shift costs	0	121,2	0	0	0	0
Total idle costs	2248	0	0	0	0	0
Total component inventory costs	496,68	119,40	0	0	0	0
Cost of lost sales "A"	65000	34900	0	0	0	0
Cost of lost sales "B"	24800	0	0	0	0	0
Total additional costs	10000	0	0	0	0	0
Total costs	149372,70	190810,60	142516	111556	127913	149210
Decision variables						
Production "A"	0	2302	2198	1200	1600	2000
Production "B"	272	998	700	720	680	780
Production "C"	320	300	350	400	450	580
Component "a" required	1680	16800	14840	10000	11850	14480
Component "b" required	10200	16000	16000	13800	16000	16800
Component "c" required	500	1802	2198	1200	1600	2000
Component "d" required	600	1290	1050	1120	1130	1360
Component "e" required	2144	3496	3150	3440	3610	4460
Day shift hours required	50,13	320	301,47	208	250,33	310
Night shift hours required	0	6,73	0	0	0	0
Idle time	149,87	0	0	0	0	0
Inventory "b"	7480	1990	0	600	1800	0
Inventory "c"	500	0	0	0	0	0
Inventory "d"	8	0	0	0	0	0
Backlog "A"	1300	698	0	0	0	0
Backlog "B"	248	0	0	0	0	0

Table 12: Model output for scenario 1 - Using safety stock

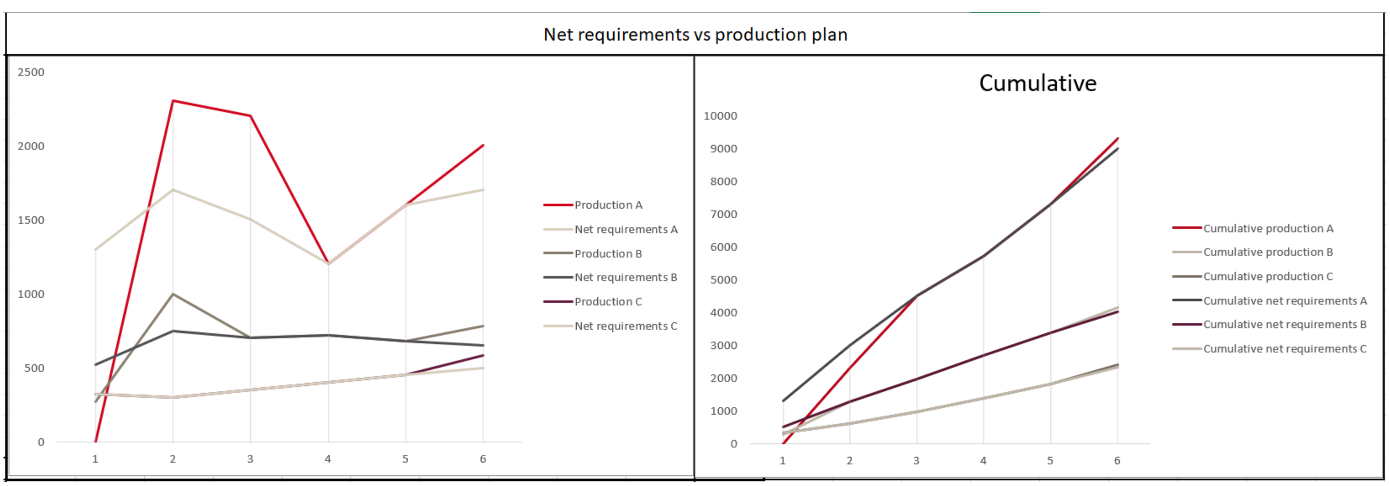

Figure 14: Scenario 1 - Net requirements vs production over time (safety stock used)

7.1.3 Expected shortage

The previous two examples have showcased the component issue on a short time notice. However, there are also occurrences where a component issue is known beforehand. As stated earlier in this report, there are limited means of evaluating the impact of such an issue. Furthermore, it is interesting to compare a known or potentially highly likely issue that occurs in the future compared to the issue occurring on a short term. Therefore, instead of the 10% component availability in period 1, the scenario is drawn up where there is 10% component availability in period 3. The results of this scenario are displayed in table 13.

Total costs = 738532,50 CHF	**Periods**					
Costs (in CHF)	*1*	*2*	*3*	*4*	*5*	*6*
Total purchasing costs	143600	145700	66398	109252	121650	125350
Total day shift costs	3650	3750	3394	3201	3755	3950
Total component inventory costs	772,50	1410	0	0	0	0
Cost of lost sales "A"	0	0	2700	0	0	0
Total costs	149372,70	190810,60	142516	111556	127913	149210
Decision variables						
Production "A"	1600	1700	1446	1254	1600	1700
Production "B"	650	750	700	720	680	650
Production "C"	400	300	350	400	450	500
Component "a" required	16800	16800	1680	10270	11850	12250
Component "b" required	14500	16000	14230	13470	14800	15000
Component "c" required	1600	1700	1446	1254	1600	1700
Component "d" required	1050	1050	1050	1120	1130	1150
Component "e" required	3300	3000	3150	3440	3610	3800
Day shift hours required	243,33	250	226,27	213,40	250,33	263,33
Night shift hours required	0	6,73	0	0	0	0
Idle time	149,87	0	0	0	0	0
Inventory "a"	5150	9400	0	0	0	0
Backlog "A"	0	0	54	0	0	0

Table 13: Model output for scenario 1 - Expected future component issue

From the results it is clear that if the component issue is known beforehand, an appropriate production plan can be set up to minimize the impact. Compared to the baseline performance, the additional costs for this scenario is only 5000 CHF. Based on the fact that the material issue is considerable, the actual impact is very minimal if prepared accordingly. For this scenario, the output suggests that the best way to prepare for this issue is to stock up on component "a" in periods 1 and 2. Interestingly, in the optimal scenario, there is still a backlog in period 3 for end-product "A". This means that, even with the issue being known beforehand, a certain level of backlog could not be avoided due to the maximum order quantity which can be seen in figure 15. The graphs displaying the net requirements vs the production plan is displayed in figure 16. This closely resembles the graphs for the baseline performance.

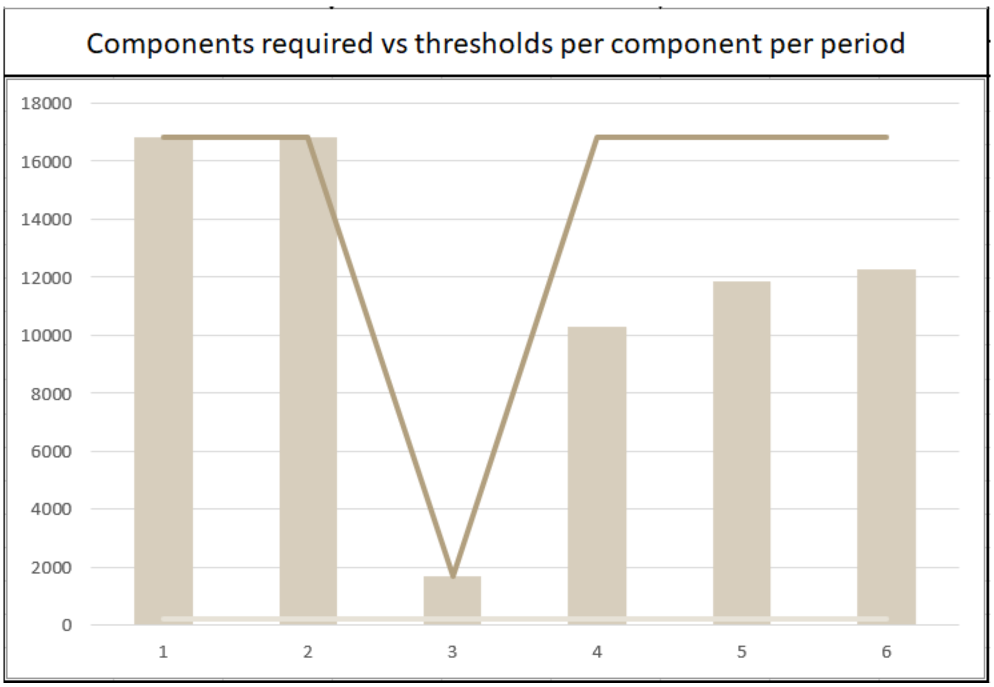

Figure 15: Scenario 1 - Component "a" required vs minimum and maximum order quantity per period (Expected shortage)

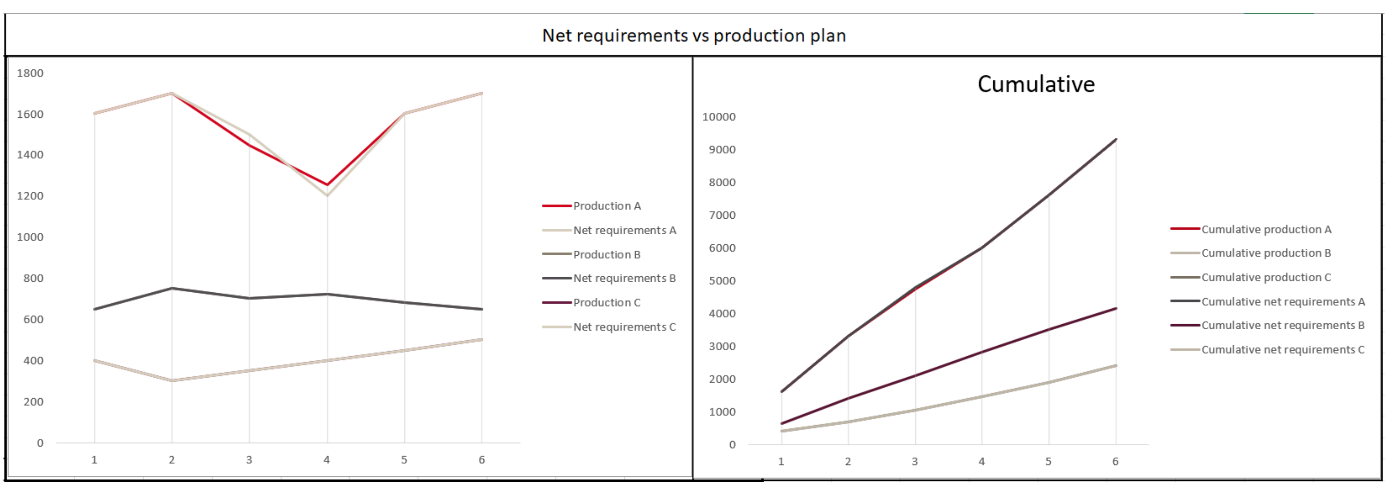

Figure 16: Scenario 1 - Net requirements vs production over time (Expected shortage)

From this investigation it becomes clear that an unexpected component issue can have severe repercussions for the future periods. The analysis also reveals that an issue with a specific component propagates to different components and even other resources. Taking damage control measures, such as using safety stock, can be a viable option to alleviate the immediate pressure caused by this issue. Furthermore, it was found that when a material issue is known beforehand, one can act accordingly to minimize the impact of such an issue.

7.2 Scenario 2: Reduction in labour hours

For the second scenario, the labour resource will be investigated. For this scenario, the labour hours are reduced to 12.5% for period 1. Additionally, the workforce will be reduced by 50%. This results in a workforce of 5 and available shift hours of 80, 40, 16, 16 and 8 for day, night, Saturday, Sunday and holiday shifts, respectively. The associated costs for the shift types are 15, 18, 20, 25 and 35 CHF per hour for day, night, Saturday, Sunday and holiday shifts, respectively. Additionally, the cost for borrowing an extra worker is negligible. The main reason for doing so is that there is usually no additional cost of borrowing an extra worker. When a worker is borrowed, they are temporarily part of the workforce and therefore get paid per shift hour. The results of this scenario can be found in table 14.

Total costs = 818001,70 CHF	**Periods**					
Costs (in CHF)	*1*	*2*	*3*	*4*	*5*	*6*
Total purchasing costs	92220	150080	115450	107200	121650	125350
Total day shift costs	600	4800	3475	3120	3755	3950
Total night shift costs	360	1681,20	0	0	0	0
Total Saturday shift costs	160	0	0	0	0	0
Total Sunday shift costs	200	0	0	0	0	0
Total holiday shift costs	137,67	0	0	0	0	0
Total component inventory costs	1092,84	0	0	0	0	0
Cost of lost sales "A"	80000	0	0	0	0	0
Cost of lost sales "C"	2720	0	0	0	0	0
Total costs	177490,50	156651,20	118925	110320	125405	129300
Decision variables						
Production "A"	0	3300	1500	1200	1600	1700
Production "B"	650	750	700	720	680	650
Production "C"	366	334	350	400	450	500
Component "a" required	7400	16800	11350	10000	11850	12250
Component "b" required	14500	16000	14500	13200	14800	15000
Component "c" required	500	2800	1500	1200	1600	1700
Component "d" required	1016	1084	1050	1120	1130	1150
Component "e" required	3130	3170	3150	3440	3610	3800
Day shift hours required	40	320	231,67	208	250,33	263,33
Night shift hours required	20	93,40	0	0	0	0
Saturday shift hours required	8	0	0	0	0	0
Sunday shift hours required	8	0	0	0	0	0
Holiday shift hours required	3,93	0	0	0	0	0
Amount of borrowed workers	4	0	0	0	0	0
Inventory "a"	3784	0	0	0	0	0
Inventory "b"	8000	0	0	0	0	0
Inventory "c"	500	0	0	0	0	0
Backlog "A"	834	0	0	0	0	0
Backlog "C"	34	0	0	0	0	0

Table 14: Model output for scenario 2

As expected, the significant reduction in labour hours results in the inability to fully cover the net requirements for period 1. It is however interesting to see that the special shifts are also utilized in this scenario. The dashboard view of the distribution of hours can be seen in 17. Based on the output, one can deduce that it is still cheaper to use these special shifts than to take on lost sales. Additionally, even though the workforce is also reduced, the model indicates that borrowing four additional workers from the pool of available workers is sufficient for production of all end-products on this line. Furthermore, this example shows the production priority of end-products when the labour resource is low. In this case, end-product "B" has the highest priority with "C" second and "A" last. This coincides with one's intuition as the cost of lost sales are the highest for "B". In the case of the component shortage however, it was found that end-product "C" was prioritized over "B". This provides an important insight as the priority of production of end-products is truly context-specific. The model also indicates that the amount of holiday shift hours required is 3,93. The reason for this is that the production of any product in this product line takes more than 0.07

hours. In practice though, an additional unit of "A" can be made in this small amount of time to reduce the backlog by 1. Finally, it can be seen that the backlog is fully recovered in period 2, as also shown in figure 18 which is facilitated by buying and therefore keeping additional components of "a" and"b" to facilitate the overproduction in period 2.

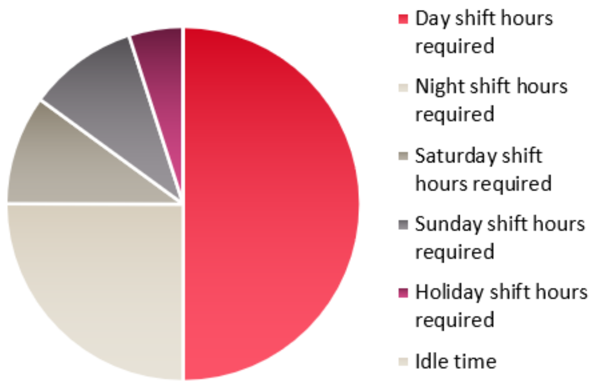

Figure 17: Scenario 2 - Dashboard view of the distribution of the shift types hours used in period 1

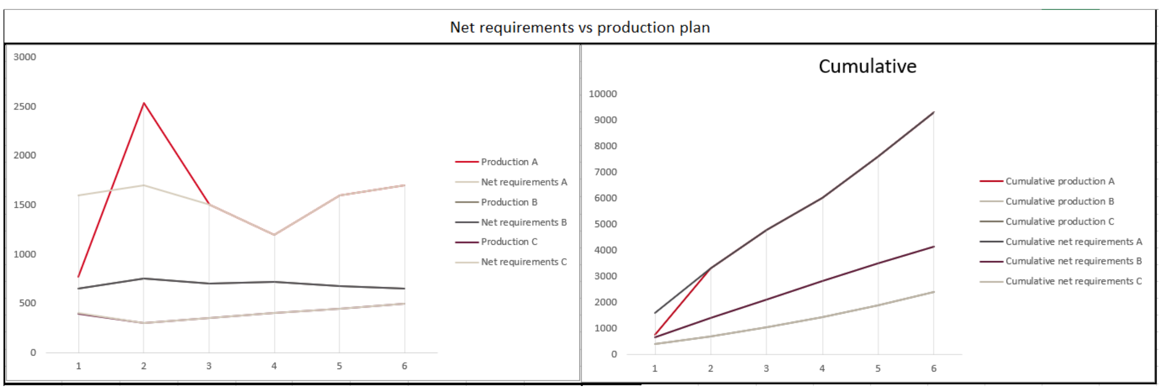

Figure 18: Scenario 2 - Net requirements vs production over time

An important note to make with scenario analyses concerning the labour resource is the qualitative aspect. As stated in section 4.2.2, worker's motivation is an important source of information in determining whether a solution is feasible. It is therefore always advised to consult with the plant representatives whether the model's solution works in practice. If it does not, the cost parameters of the different shifts might need to be adjusted upwards to incentivize the workers.

7.3 Scenario 3: Uncertainty in component arrival

The final scenario discussed in this section relates to the uncertainty of component arrivals. More specifically, how the uncertainty of the arrival of one component affects the other required components. Take for instance a component with a long lead time. This component has to be ordered further in advance than a short lead time component such that it arrives on time for production. Just before the pre-S&OP occurs, one of the material representatives receives the news that the component with a long lead time might not arrive on time for production in the next period. At this point, the material representative has no yet ordered the other components required for production as they have a short lead time. In these scenarios, the material's representative faces a tough decision; should they order the the components with the short lead time or not? Essentially, the material's representative tries to balance the risk of not being able to produce by not ordering the short lead time components and the risk of excess inventory costs if the long lead time component does not arrive. Due to Hilti's demand driven focus, the latter part of the trade-off is often overlooked. Therefore, the material representatives are often committed to ordering the short lead time components which has resulted in high inventory costs in the past. To replicate this scenario, component "a" is set to be the component with a long lead time and the potential issue. This issue is equivalent to the one described in scenario 1, where the quantity of this component is expected to be 10% (1680) of the maximum order quantity for that period. However, in this scenario the material's representative assumes that the issue will not occur and therefore does order the short lead time components. The optimal order quantity when there is no issue was already determined in the baseline performance and can be found in table 10. Therefore, the CPs order quantity for the short lead time component ("b", "c", "d" and "e") is equal to the required amount of components in the baseline scenario. To replicate this in the model, the minimum order quantity parameter in period 1 is set to the required components when the production line is not facing an issue in period 1 as displayed in table 10. This results into minimum order requirements of 14500, 1600, 1050 and 3300 for components "b", "c", "d" and "e", respectively. Now it is assumed that the long lead time component ("a") in fact does not arrive. This results into changing the maximum order quantity parameter of "a" to 1680. The result of this scenario can be found in table 15.

Total costs = 916495,40 CHF	**Periods**					
Costs (in CHF)	*1*	*2*	*3*	*4*	*5*	*6*
Total purchasing costs	68000	138728	148970	109252	121650	125350
Total day shift costs	856	4800	4800	3201	3755	3950
Total night shift costs	0	33,60	372	0	0	0
Total idle costs	2144	0	0	0	0	0
Total component inventory costs	1096,80	237	0	0	0	0
Cost of lost sales "A"	80000	57200	2700	0	0	0
Cost of lost sales "B"	39400	0	0	0	0	0
Total costs	176335,20	215718,60	156842	112453	125405	129300
Decision variables						
Production "A"	0	2156	2590	1254	1600	1700
Production "B"	256	1144	700	720	680	650
Production "C"	400	300	350	400	450	500
Component "a" required	1680	16800	16800	10270	11850	12250
Component "b" required	14500	14230	16000	13470	14800	15000
Component "c" required	1600	556	2590	1254	1600	1700
Component "d" required	1050	1050	1050	1120	1130	1150
Component "e" required	3300	3000	3150	3440	3610	3800
Day shift hours required	57,07	320	320	213,4	250,33	263,33
Night shift hours required	0	1,87	20,67	0	0	0
Idle time	142,93	0	0	0	0	0
Inventory "b"	11940	3950	0	0	0	0
Inventory "c"	1600	0	0	0	0	0
Inventory "d"	394	0	0	0	0	0
Inventory "e"	788	0	0	0	0	0
Backlog "A"	1600	1144	54	0	0	0
Backlog "B"	394	0	0	0	0	0

Table 15: Model output for scenario 3

From the output it can be deduced that the results are very similar to scenario one with no damage control. The key difference in this case is that additional inventory costs were made because the material representative anticipated that the long lead time component would arrive. In this instance it can be derived that this was the correct call to make as the inventory costs are negligible for this production line. However, one can imagine that for a larger production line with higher quantities of components this choice is more difficult to make. Additionally, the cost structure of the storage of components is not linear as described in section 5. This cost structure follows a piece-wise linear function and therefore the excess in components leads to significantly higher costs in practice. However, there is another important metric to judge this scenario on which are the purchasing costs. In the previous scenarios the purchasing costs were not that insightful as all components were bought in an optimal way. However in this scenario, unnecessary inventory is kept which means that capital is tied up in this inventory. In this case, the monetary value of the unused inventory is roughly 15000 CHF. It is difficult to quantify how detrimental it is to have this capital tied up in inventory. Essentially, the two main drawback are 1) the capital cannot be invested elsewhere and 2) risk of obsolescence. Therefore, when a scenario as described here occurs, these factors are important to account for. Additionally, this analysis highlights that a good understanding and evaluation of both risks for both parties is essential in making the best decision. Ultimately, the 'best' decision is the one where both risks are understood and accepted resulting in a final decision which is mutually supported by both parties.

7.4 Case study conclusion

This section has illustrated the use of the model by means of realistic case studies. From the results, it became evident that the impact of lacking one resource can have detrimental effects on the production and on other resources. Furthermore, the case studies and the way they are analyzed provide a solid foundation for the CPs to enhance their own decision-making ability using this model. The central theme with the scenarios which were discussed and analyzed was transparent communication with the stakeholders. The first study provided key insights into the impact of component shortage. There is a significant difference between knowing an issue in advance compared to an issue arising unexpectedly. It was further more shown, when the issue was unexpected, using measures such as the safety stock can be effective in reducing the impact of an issue even when a penalty was applied. The second study discussed the impact of labour shortage. It was found that the priority assigned to the production of end-products was different in the first scenario. This showcased that, even with the cost of lost sales the same for each end-product, the prioritization of end-products is not clear-cut and therefore context specific. The scenario furthermore highlighted the importance of the unique qualitative aspect of this resource which should always be considered to determine whether the proposed optimal solution is feasible in practice. This section was concluded by highlighting a scenario where the CP and the material representative have conflicting interests. The scenario under consideration had a suspected material issue which led to the dilemma for the material's representative of ordering the additional required components or not. Not ordering would potential save inventory costs if the problematic component would in fact not arrive at the risk of losing sales if the problematic component did arrive. Additionally, an important aspect which could be overlooked in this scenario is the capital investment. After all, money gets tied up in unused inventory which exposes the company of obsolescence risk. In order to navigate such a scenario, it is advised to objectively investigate both risks and mutually decide on the best approach forward. Summing up, the model helps in providing the quantitative support to shed light on and discuss scenarios and ultimately make an agreed-upon best solution. It should be emphasized here that the model/tool functions as a support tool. Ultimately, the capacity related decision is made by the CP in close collaboration with the present stakeholders.

8 Scalability

For Hilti, one of the main requirements of the model was that the model could be implemented and executed for different production lines and plants. In other words, Hilti wants the model to be scalable. Law (1998) provides a very simple way of describing scalability namely the ability to "simulate more entities". In this context, the entities can be interpreted in two ways. First, the scalability of the model to more plants and second the scalability of the model to more products. The first relates more to the generalizability of the model whilst the second relates to the way the model is programmed.

Scalability of the model

The assessment of whether the model complies with the requirement of being scalable to other production lines and plants starts in the model's conceptualization phase. In section 6.2.1, the model's conceptual validity was discussed which can serve as an initial indicator of the model's scalability. However, the model being conceptually valid is not sufficient to prove its scalability. After all, a model can be conceptually valid by including all details in a specific environment. In this case, including the details will increase the conceptual validity but reduce the scalability. For this project, the initial focus was to generate a model which could be scaled up as described in section 1.5. Therefore, the approach was to include as many different perspectives as possible. In practice, this resulted in meetings with different stakeholders which operated in different plants and different BUs. The information gained from these meetings was closely examined for commonalities and ultimately synthesized to produce the conceptual and subsequent mathematical model as detailed in section 5. This approach led to the omission of plant and/or production line related details which further supports the generalizability of the model. The fact that this model was deemed to be conceptually valid by the stakeholders provides a good indication that the model is scalable to other production lines and plants as well. Furthermore, the model accounts for both tool and assembly based plants. Although the constraints related to the machine resource are limited, a machine based plant can still utilize the model to gain relevant insights. This is also due to the option to manually adjust to model to fit the model to the environment. For instance, the generic model includes five types of shifts namely day, night, Saturday, Sunday and holiday shifts. If a plant has different shift types, these names can be interchanged as the model is not bound to these specific names. Additionally, the constraints and parameters can leave room for interpretation. For instance, if a production line does not require a specific team size but instead needs a specific amount of special operators, the constraint does not have to be adjusted. In this way, this constraint can be used to ensure that the bottleneck, which in this case would be the amount of special operators required, is accounted for. One important feature that should be mentioned here is the model's ability to aggregate production lines. Essentially, the model can account for multiple different production lines as long as they share the same resources. Additionally, there should not be any interdependencies between resources which are currently not covered by the constraints. This means that in practice, it has to be determined first whether the model still accurately represents the environment before one can aggregate production lines.

Scalability of the program

In order to classify the model as a scalable model, it is also important to investigate the inner workings of the model. After all, a model could be scalable in theory but lack the proper mechanisms to do so in practice. For this project, this process is described in section 6.2 and section 6.3. In the first section, it was explained that the mathematical model was be implemented in Python. Whilst Python is a very suitable environment for executing and creating the program, the actual process of retrieving and outputting data in this environment was sub-optimal. For this reason, it was decided to move the required data to run the model to Excel. This decision favours the ability to scale the model as inputting data manually in Python can be very inefficient and cumbersome. Additionally, the ERP system can output the relevant data in an Excel format which further removes the need for manual interference. In order to ensure that the data was properly extracted from Excel, changes were made to the program accordingly. This resulted in the ability to extract all the data within a prespecified range of Excel cells. For example, one can easily extract all components of a specific production line from the ERP system and format it in a column. The model is coded in such a way that all these components can be immediately extracted and are formatted correctly such that the model can be executed. If one were to add one additional component, the only thing that has to be changed is the data range within Python. Therefore, even with very complex BoMs, the data can still be easily extracted and used for model execution. This combined with a powerful solver implemented in Python makes the execution of the program swift and efficient.

It can be concluded that there is positive indication that the model can be scaled to different production lines and plants. From the start, the intent was to create a generic model which was therefore suitable to be scaled up. The process that followed was designed to accomplish this goal by taking into account different perspectives from different plants and BUs. The results were synthesized and validated by the stakeholders which reflects positively on the model's scalability. Additionally, the method used to program the model allows the introduction of more or different parameters and values if necessary. It is however important to recognize that, if one wants to aggregate production lines, one inspects the environment first to ensure the model remains valid.

8.1 Practical guidelines for implementation

To conclude this section, recommendations will be provided to ensure that the model can be used in practice. These recommendations can be used as a guideline to steer the implementation process in practice.

- Prepare the Python environment. Since the model uses Python as a means to execute the model, the Hilti computers have to be equipped with Python to run this model. Alternatively, a different environment can be used to execute the code but one has to be aware of potential differences in the coding language. To ensure a smooth implementation, it is therefore advised to download Python, and the packages required which are PuLP and OpenpyXL, beforehand such that the model can be directly implemented.
- Training. After the model is properly grounded in the Hilti environment, the end-users, which are the CPs in this case, should be trained to use the tool. This can be done using the data of the hypothetical production line which is detailed in Appendix D. The practical steps which are required to execute the model are the following:
  - 1. Ensure that the Python file containing the code and the Excel sheet containing the data are in the same folder.
  - 2. Modify the executable file such that the correct paths are accessed.
  - 3. Open the Excel file to make a scenario (by adjusting the cells marked green in the datasheet).
  - 4. Save and close to Excel file. Make sure that the data sheet is the last accessed sheet.
  - 5. Click on the executable file. A window will be opened (command prompt). Do not interrupt the program whilst it is running. When it is done running, the following message will be displayed: "Press any key to continue".
  - 6. Close the window by pressing any key or simply exiting out.
  - 7. Open the Excel file. The output will be displayed in the "Results" sheet.

It should be noted here that steps 1 and 2 only have to be performed once before using the model. The goal of the training is to make the CPs familiar with the tool's execution and the output it produces. Furthermore, to oversee this process of training, a person should be appointed to be the process expert. This person is the central points of contact for any questions related to the tool. Additionally, this person maintains the tool and, when applicable, improves the tool based on the CPs feedback.

- Determine and delineate input data. In parallel to training the CPs, the actual data of the production lines can be extracted from the ERP and inputted into the respective datasheet. It is important here that the prespecified range in which data is selected, as coded in Python, is configured accordingly. Preferably, the process expert would be responsible for this task. It therefore requires the process expert to have a good understanding of both the model and Python. After the configuration, the CPs ought to test the model again to ensure its validity. Once the validity is established, the implementation can be considered to be successfully completed.

9 Discussion

This project has provided a tangible decision-support tool for capacity planning in a manufacturing environment. From the start, the main goal was to develop and integrate a practical tool which provides the end-user with quantitative support for developing and assessing different scenarios. With the completion of this goal, it is important to reflect on the project. This will be done by first revisiting the research question as defined in section 1.4. A comprehensive answer will be provided to this research question by discussing each sub research question. After that, the limitations of the proposed model, and also this project, will be discussed. Subsequently, recommendations will be made to Hilti to further improve and enhance their S&OP process. This section will be concluded by highlighting the contributions of this project and providing future research directions.

9.1 Conclusions

This section aims to provide an answer to the main research question:

How can scenario analysis be incorporated and operationalized into a decision-support tool which supports the central planner in making capacity related decisions in the S&OP process?

In doing so, the sub research questions are revisited and answered. The first sub research question was the following:

Sub question 1: What parameters are key in making decisions in the current process?

To answer this question, a thorough investigation was conducted into the current decision-making process. The main way of gathering information was through attending (pre-)S&OP meetings and observing the discussions between the stakeholders. Ultimately, the decision was driven by a focus on customer satisfaction. Therefore, one can deduce that the most important parameter is essentially the cost of lost sales. Other costs related to production were also considered but usually to a lesser degree. Additionally, the parameters related to three critical resources (material, man power and machine) played a key role in determining the production capability. The resource where the issues were the most prevalent was (and is) material. A detailed description of all identified parameters can be found in section 4.

Sub question 2: What tools are currently being used to aid the central planner in making decisions?

The investigation conducted to answer the previous sub research question also provided an answer to this question. Additionally, 1-on-1 interviews with the CPs were held to gain more insights into the development of scenarios. Essentially, there is one tool available to assist the CP which is a financial scenario template. This template contains the main cost parameters which the CP can and should consider when making scenarios. However, filling in the values is a manual process. Additionally, the parameters concerning the resources are unaccounted for in this template. Therefore, in practice, this template is often not used. This results in the CP developing their own tool which is usually takes the form of an overview of the most relevant information from their perspective.

Sub question 3: What are the most common challenges currently faced by the CPs during the decision-making process?

The answer to this question marked the end of the initial investigation of the S&OP decision-making process and provided a valuable starting point for the solution. There were several challenges identified. First, the development of scenarios, which forms the basis for discussion during the pre-S&OP, is a time-expensive effort. This is largely due to the difficulty in retrieving the relevant data. Second, it is difficult for the CP to find the 'best' scenario. This is due to the high complexity involved as there are many interdependencies between the relevant parameters. Finally, the scenarios which are proposed by the CP in the pre-S&OP are often challenged by the stakeholder as they may perceive them as 1) inaccurate and/or 2) unfavourable. Ultimately these challenges can be resolved if there was a quantitative support tool or framework which can assist the CP in developing and assessing scenarios in a timely and transparent fashion.

Sub question 4: How can the tool be developed to ensure user-friendly interaction?

The most crucial part in ensuring an end-user friendly interaction with the tool was the selection of the environment. Initially, it was chosen to implement the model in Python. Whilst this environment was very suitable for model execution, it did not meet the requirement of end-user friendliness. Therefore, the data input and output was integrated into Excel. To fully complete the integration from Python to Excel, an executable file was created such that the CP did not have to interact with the Python environment. Integrating the model into Excel has the benefit of being accessible and understandable whilst Python requires a certain level of pre-knowledge. Additionally, Excel makes it easier to manipulate the input data to create scenarios which is crucial for the end-user. Moreover, it is important that the model is not a black box. The CP needs to have the ability to derive the output manually which is made possible due to the deterministic nature of the model. It is also important that the results are easily obtained and analyzed which is facilitated in Excel. The process of analyzing the results was further enhanced by providing the CPs with a visualization of the key results and complimentary insights by means of a performance dashboard. Throughout this process, iterative feedback meetings with the CPs were crucial to ensure that their needs were accounted for.

Sub question 5: How can the performance of the decision-support tool be measured?

The final sub question can be interpreted in two-ways. First, the performance of the tool itself and second the performance of the output of the tool. For the latter, the performance dashboard was created. This performance dashboard includes a variety of KPIs related to all resources and the production plan. Based on these KPIs, the CP can more efficiently compare scenarios. Due to time restrictions, the full development of the performance dashboard was not possible. However, the performance dashboard as described and implemented serves as a solid foundation to expand upon. The performance of the tool itself is difficult to estimate. After all, the tool serves as a decision-support tool instead of a decision-making tool. Moreover, there is currently not a comparable tool in place to use as a benchmark. Therefore, the most appropriate measures of performance are in this case the utilization of the tool and the amount of time spent developing and assessing scenarios. A higher utilization of the tool suggests that the tool is considered to be practical and relevant. For the latter, anecdotal evidence provides ample of support for the improvement of the decision-making process based on the time saved when using the tool.

9.2 Limitations

In this section the limitations of the project and the proposed model will be discussed. The main limitation of the model is that it is designed for a single production line. Essentially, this means that the model provides a local optimal solution instead of a global optimal solution. This is due to the fact that the model does not account for full resource sharing. In practice, this translates to, for example, the availability of components being delineated per production line. For this example specifically, it would be better to know the total demand for a component for all production lines such that the allocation of the component could be performed accordingly.

The second limitation is partly related to the first limitation as currently the model does not consider the ability to produce end-products on different production lines. In practice, there are examples of end-products which can be produced on different production lines. Even though this does not hold for all end-products, it does provide a way of better balancing capacities. In the end, it is beneficial (when possible) to balance production lines with overcapacity with production lines with undercapacity which is currently unaccounted for.

The third limitation concerns the way the CP interacts with the tool. Currently, the CP manually adjust the values in the datasheet in Excel. After that, the CP exits the Excel sheet and runs the model using the executable file. This takes extra time which can be avoided if the model was better integrated. Additionally, the model could be more dynamic. Currently, the impact on the production capabilities can only be seen after the model is ran. Preferably, the CP could adjust a parameter value and immediately see the impact of this adjustment on the other parameters and relevant KPIs. This combined with the incomplete performance dashboard is limiting the CP in accessing more relevant and timely information which might be able to help the CP provide a more complete picture of the scenario under consideration.

9.3 Recommendations

Throughout the process of conducting this project, several discoveries were made which were not (fully) discussed. Therefore, this section is dedicated to briefly expand upon these discoveries. In order to reap the most benefits out of this project, the following recommendations are made:

- Focus on data quality. This point is related to the input data of the model. It is of utmost important that the input data is accurate and valid. After all, the model's accuracy is directly linked to the input data. Managing and validating the input data is therefore a primary task of the process expert to ensure proper functioning of the model.
- Foster a collaborative atmosphere. The operation of the model relies on the input of both the plant and the material representatives. Therefore, exchanging information between stakeholders in a timely fashion is central to a successful S&OP process. It should therefore be emphasized that every stakeholder plays a unique and invaluable role in the S&OP process.
- Organize evaluation meetings. After the model has been integrated, it is recommended to organize evaluation meetings. The purpose of these meetings is to critically evaluate the model such that the process expert can make adjustments accordingly. These meetings should be led and organized by the process expert once every month after the S&OP meeting. The frequency of these meetings can be reduced after the model has been properly established in the organization.
- Invest in data maintenance. From the investigation described in section 4, it was found that when there is an issue with a component, the data is not stored after the issue is resolved. It is important to develop a procedure or framework to ensure that this data is properly stored. This data can be crucial as these components might require active monitoring for specific periods. Additionally, this data can provide an indication for future problems which can be used to enhance the predictive capabilities of the model.
- Involve other departments. Finally, it is important to consider involving other departments into the S&OP process. However, this should only be done if it is beneficial to the decision-making process. For example, when a new product is introduced, it might be beneficial to invite the business department. The representative of this department can provide further details about the prospects of this product which can lead to valuable insights which benefits the decision-making process. Another example is the sales department. Whenever a CP has overcapacity on their production line, it might be interesting to discuss a potential price reduction with a sales representative. This way, the overcapacity can be used to fulfill an expected increase in demand if a price reduction is applied.

9.4 Contributions & Future research

The contributions of this project can be categorized into two categories: practical and academic. From a practical perspective, this project has provided a tangible and end-user friendly decision-support tool which supports the CP in making capacity related decisions in the S&OP process. With the introduction of this tool, Hilti can encourage a new standard way of working which applies for all production lines and plants. The tool has tackled the most prevalent challenges Hilti faced during the S&OP process which was 1) lack of time, 2) difficulty to retrieve required data and 3) high complexity. Additionally, the tool can be used in case of imminent resource issues or future resource issues, highlighting its ability to be both reactive and proactive. Finally, the tool helps Hilti progress in S&OP maturity. From an academic perspective, this thesis aimed to fill the gap as identified by Pereira, Oliveira, and Carravilla (2020). To reiterate, the authors identified a lack of generic modelling approaches. This thesis contributes to fill this gap by providing a structured way of defining, implementing and integrating a S&OP decision-support tool. Additionally, the generic model as defined in this thesis can serve as a foundation for different companies in a manufacturing environment. Furthermore, the ability to develop and integrate this model can be incorporated in the vast amount of maturity frameworks available in literature, such as the one developed by Grimson and Pyke (2007). Finally, the thesis aimed to contribute in the investigation of a holistic way of measuring performance in the S&OP process.

The contributions and limitations are conducive to discussing the future research direction in the field of S&OP decision-support tools. First, additional research is required into a holistic way of measuring and displaying S&OP performance. This thesis has made a start in the development of a performance dashboard, but further research is required to determine how a performance dashboard can be optimally shaped to facilitate the transfer of information. Second, the proposed filter for the input data should be researched and developed. This filter helps in reducing the complexity of the model and should be focused on filtering out components which are not relevant for investigation. How to determine whether a component should be filtered out is therefore a topic for further investigation. Third, as discussed in the limitations, future research should investigate the expansion of the model to include more production lines. In doing so, it is important to identify and correctly formulate the additional interdependencies which emerge due to the aggregation of production lines. However, it is important to not over-constrain the model as the model should still be practically significant and user-friendly. It is therefore up to future research to strike the right balance between accuracy and complexity. Finally, the model should be tested in different manufacturing environments. This way, the model can be enhanced and validated which ultimately leads to a widely accepted generic model which can be used as a baseline for capacity related decisions in any manufacturing environment.

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10 Appendix

Appendix A: Visual representation of main datasheet in Excel

Costs

Component costs		
Component	*Purchasing price*	*Storing cost*
a	5	0,25
b	2	0,2
c	3	0,15
d	12	0,2
e	4	0,25

Product costs		
End_product	*Cost of lost sales*	*Storing cost*
A	50	2
B	100	4
C	80	3

Labour costs			
Shift type	*Cost per shift type (hour)*	*Period*	*Cost of borrowing 1 worker*
D	15	1	0,0001
N	18	2	0,0001
Sa	20	3	0,0001
Su	25	4	0,0001
Ho	35	5	0,0001
		6	0,0001

Main dashboard						
Net requirements	1	2	3	4	5	6
A	1000	900	800	1000	1000	900
B	800	700	800	500	900	1000
C	500	600	800	700	400	500
Max_machine_hours	1500	1500	1500	2000	1500	1500
Min labour hours	0	0	0	0	0	0
Max labour hours	640	640	640	640	640	640
Workforce	8	9	9	9	9	9
Pool of available workers	15	15	15	15	15	15
Total shift hours available						
D	320	320	320	320	320	320
N	160	160	160	160	160	160
Sa	64	64	64	64	64	64
Su	64	64	64	64	64	64
Ho	32	32	32	32	32	32
Maximum component availability						
a	16800	16800	16800	16800	16800	16800
b	16000	16000	16000	16000	16000	16000
c	16200	16200	16200	16200	16200	16200
d	16900	16900	16900	16900	16900	16900
e	16800	16800	16800	16800	16800	16800
Minimum component availability						
a	200	200	200	200	200	200
b	400	400	400	400	400	400
c	500	500	500	500	500	500
d	600	600	600	600	600	600
e	400	400	400	400	400	400

End products	Current inventor	Current backlog
A	0	0
B	0	0
C	0	0
Components		
a	0	
b	0	
c	0	
d	0	
e	0	

Production capabilities	**Machine**	**Labour**
A	2	10
B	2	15
C	10	10

Figure 19: Visual representation of the main data sheet in Excel

Appendix B: Complete final mathematical model formulation

Minimize costs:

$$Min \sum_{t=1}^{T} \sum_{c=c}^{C} \sum_{e=e}^{E} \Big(hdr_t * CDS + hns_t * CNS + CSA * hsa_t + CSU * hsu_t + CHO * hho_t + CHI * hi_t + mr_{c,t} * CPU_c + ie^{+}_{e,t} * CI_e + ic_{c,t} * CI_c + CLS_e * ie^{-}_{e,t} + AC_t \Big) \quad (38)$$

Maximize service level:

$$Min \sum_{t=1}^{T} \sum_{c=c}^{C} \sum_{e=e}^{E} \Big(hdr_t * CDS + hns_t * CNS + CSA * hsa_t + CSU * hsu_t + CHO * hho_t + CHI * hi_t + mr_{c,t} * CPU_c + ie^{+}_{e,t} * CI_e + ic_{c,t} * CI_c + M_e * ie^{-}_{e,t} + AC_t \Big) \quad (39)$$

The model is subject to the following constraints:

State of inventory

$$ie_{e,t} = ie^{+}_{e,t} - ie^{-}_{e,t} \qquad \forall e \in E, t \in T \quad (40)$$

Conservation of flow (end-products)

For t = 1:

$$ie_{e,t} = SIE_e - SB_e + p_{e,t} - NR_{e,t} \qquad \forall e \in E$$

For t = 2,3,4,5:

$$ie_{e,t} = ie_{e,t-1} + p_{e,t} - NR_{e,t} \qquad \forall e \in E \quad (41)$$

For t = 6:

$$ie_{e,t} = ie_{e,t-1} + p_{e,t} - NR_{e,t} + DI_{e,t} \qquad \forall e \in E \quad (42)$$

Conservation of inventory (components)

For t = 1:

$$ic_{c,t} = SIC_e + mr_{c,t} - B_{c,e} * p_{e,t} \qquad \forall e \in E, c \in C$$

For t $\neq$ 1:

$$ic_{c,t} = ic_{c,t-1} + mr_{c,t} - B_{c,e} * p_{e,t} \qquad \forall e \in E, c \in C \quad (43)$$

Upper and lower bounds - Material

$$E^{min}_{c,t} \leq mr_{c,t} \leq E^{max}_{c,t} \qquad \forall c \in C, t \in T \quad (44)$$

Upper bounds production - Machine

$$\sum_{e=e}^{E} \frac{p_{e,t}}{R_e} \leq HM^{max}_t \qquad \forall t \in T \quad (45)$$

Upper bounds production - Material

$$\sum_{e=e}^{E} p_{e,t} * B_{c,e} \leq ic_{c,t} + mr_{c,t} \qquad \forall e \in E, t \in T, c \in C \tag{46}$$

Sufficient labour

$$1 \leq TS_e \leq W_t + exp_t \qquad \forall e \in E, t \in T \tag{47}$$

Upper bound borrowed workers

$$0 \leq exp_t \leq EXP_t^{max} \qquad \forall t \in T \tag{48}$$

Upper bounds production - Labour

$$\sum_{e=e}^{E} \frac{p_{e,t}}{K_e} = hdr_t + hns_t + hsa_t + hsu_t + hho_t \qquad \forall t \in T \tag{49}$$

Upper and lower bounds labour

$$L_t^{min} \leq hdr_t + hns_t + hsa_t + hsu_t + hho_t + hi_t \leq L_t^{max} \qquad \forall t \in T \tag{50}$$

Capacity labour - types of shifts

$$\begin{aligned} hdr_t &\leq WD * AD_t & \forall t \in T \\ hns_t &\leq WN * AD_t & \forall t \in T \\ hsa_t &\leq WSA * ASA_t & \forall t \in T \\ hsu_t &\leq WSU * ASU_t & \forall t \in T \\ hho_t &\leq WHO * AHO_t & \forall t \in T \end{aligned} \tag{51}$$

Non-negativity constraint

$$hdr_t, hns_t, hsa_t, hsu_t, hho_t, hi_t, exp_t, mr_{e,t}, p_{e,t}, ie_{e,t}^{+}, ie_{e,t}^{-} \geq 0 \tag{52}$$

Integers

$$exp_t, mr_{e,t}, p_{e,t} \text{ are integer} \tag{53}$$

Appendix C: The performance dashboard

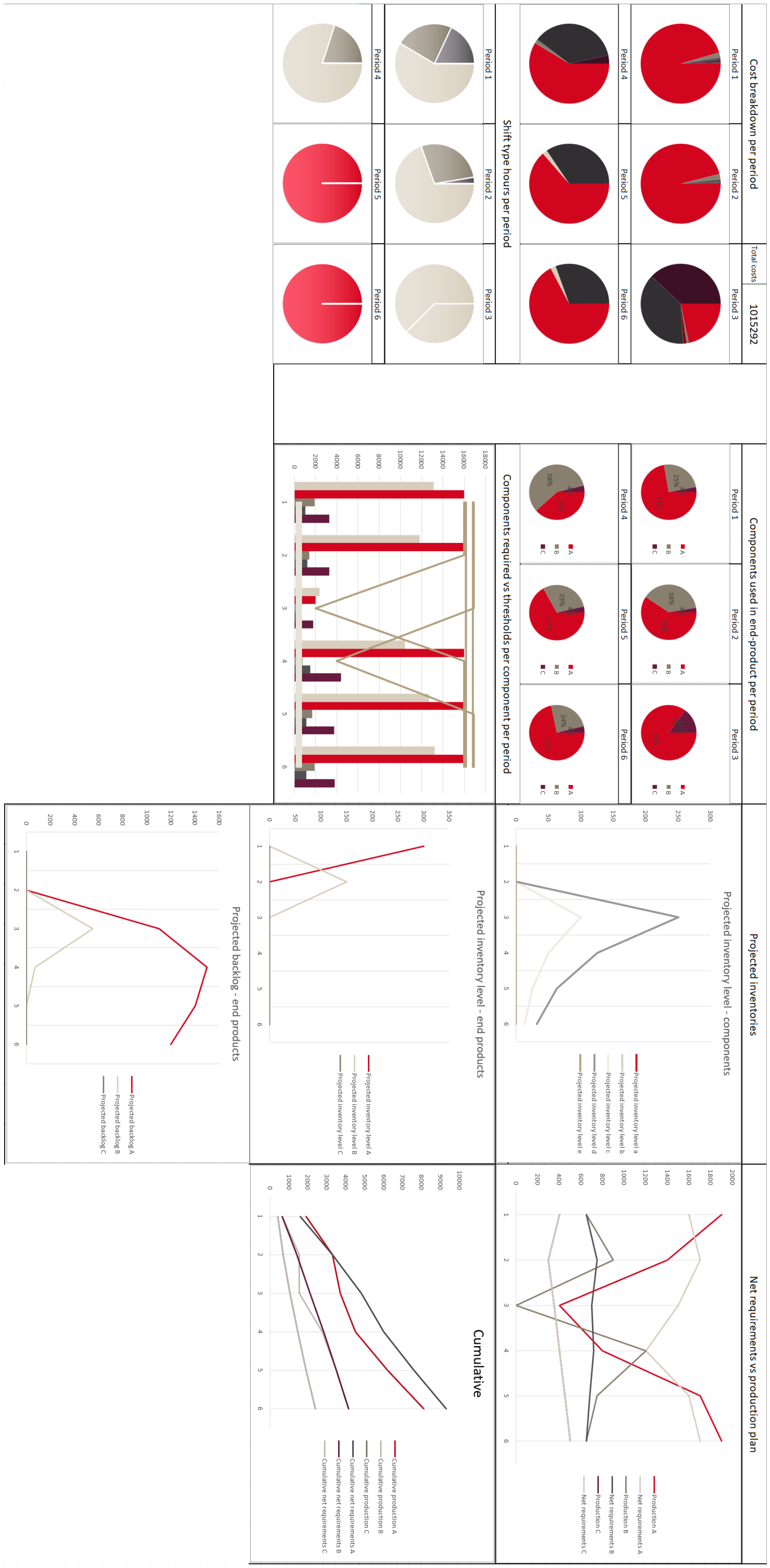

Figure 20: Detailed performance dashboard

Appendix D: Input data case study

The initial parameter values for the non-cost and non-throughput related input of the hypothetical production line can be found in 16. It should be noted here that the starting inventory of both the components and end-product is assumed to be 0. The same holds for the backlog of end-products and the desired end inventory for end-products. With regards to the shift hours available, it is assumed that there are 20 normal workdays in the month. Additionally, it is assumed that there can be two regular shifts per day and 1 night shift per day, each of 8 hour per shift. Therefore, the total available hours on a monthly basis for regular and night shifts are 20*16=320 and 20*8=160, respectively. Similarly calculations can be made for the Saturday, Sunday and holiday shifts. However, for these shifts it is assumed that night shifts cannot be used due to the overlap of days. This yields 64 hours on a monthly basis for Saturday and Sunday shifts (4 days per month multiplied by 16) and 32 hours on a monthly basis for holiday shifts (2 days per month multiplied by 16). The maximum labour hours is calculated based on these assumptions and is simply the sum of all the hours of the different shift types in this case.

For the costs of storage, a common method employed by Hilti is to take a preset percentage of the purchasing price. In this example, the storing costs for components are 3% of the purchasing price. Since end-product do not have a purchasing price, the percentage is taken from the cost of lost sales which in this case is 5%. The costs related to components and end-product are displayed in table 17. With regards to the different shift types, the following cost values are used: Dayshift = 15/hour, Nightshift=18/hour, Saturdayshift=20/hour, Sundayshift=25/hour, Holidayshift=35/hour.

Additionally, the cost of borrowing a worker is set to be a negligible amount. This is due to the fact that, when a worker is borrowed from the available pool, there is often no additional costs attached. Essentially the worker becomes part of the workforce and therefore gets paid through the shift hours. The decision variable which determines if an extra worker is required can therefore in this context be seen as a binary variable. However, there are instances where borrowing a worker does incur additional costs. It is for this reason that this decision variable is not binary and the costs can be adjusted by the CP to account for these extra costs if applicable.

Finally, the production capabilities (throughput) of the production line and the production coefficient are shown in table 18 and table 19, respectively.

	Periods					
Net requirements	*1*	*2*	*3*	*4*	*5*	*6*
"A"	1600	1700	1500	1200	1600	1700
"B"	650	750	700	720	680	650
"C"	400	300	350	400	450	500
Maximum machine hours	800	800	800	800	800	800
Minimum labour hours	200	200	200	200	200	200
Maximum labour hours	640	640	640	640	640	640
Workforce	9	9	9	9	9	9
Pool of available workers	5	5	5	5	5	5
Total shift hours available						
Day	320	320	320	320	320	320
Night	160	160	160	160	160	160
Saturday	64	64	64	64	64	64
Sunday	64	64	64	64	64	64
Holiday	32	32	32	32	32	32
Maximum components availability						
"a"	16800	16800	16800	16800	16800	16800
"b"	16000	16000	16000	16000	16000	16000
"c"	16200	16200	16200	16200	16200	16200
"d"	16900	16900	16900	16900	16900	16900
"e"	16800	16800	16800	16800	16800	16800
Minimum components availability						
"a"	200	200	200	200	200	200
"b"	400	400	400	400	400	400
"c"	500	500	500	500	500	500
"d"	600	600	600	600	600	600
"e"	400	400	400	400	400	400

Table 16: Initial values for the non cost parameters for the hypothetical production line

	Costs		
End-products	Purchasing price	Cost of lost sales	Storing costs
"A"	n/a	50	2.5
"B"	n/a	100	5
"C"	n/a	80	4
Components			
"a"	5	n/a	0.15
"b"	2	n/a	0.06
"c"	3	n/a	0.09
"d"	12	n/a	0.36
"e"	4	n/a	0.12

Table 17: Initial values for the cost parameters related to the components and end-products for the hypothetical production line

End-products	Machine	Labour
"A"	20	10
"B"	30	15
"C"	20	10

Table 18: Initial values for production capability (throughput) for the hypothetical production line

	"A"	"B"	"C"
"a"	5	5	1
"b"	5	10	0
"c"	1	0	0
"d"	0	1	1
"e"	0	2	5

Table 19: Initial values for number of components per end-product for the hypothetical production line (Production coefficient)