Developing and testing an APP model for Air Spiralo®

A master thesis by:

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Preface

As industry 4.0 starts to have its effect on the performance of production, it is important for a company to be able to analyse any changes in required capacities and inventory quickly. By increasing the performance of production, the manufacturing lead time will decrease and efficiency will go up. It also happens often that knowledge is not captured in a decision making model. As a result, this knowledge is lost when the person leaves the company. So, to follow the effects of improving efficiency in production and to capture every bit of this knowledge, it is sensible to create a decision making model that is able to make decisions on a tactical planning level and takes the objectives of the optimal solution into consideration. For this, the aggregate production planning (APP) model has proven to be very useful. This study, therefore, aims to create such an APP model and allow the company to capture every bit of knowledge from different departments into one place.

Upon completion of this master thesis, I am finishing the master program "*Production and logistics Management"* from the Industrial Engineering and Management study at University of Twente, Enschede. During this master program, I have been able to grow a lot as a person. I have become a person who is capable of leading a project as well as analysing difficult engineering problems. And also, I have grown confident in applying the theoretical knowledge from my study into day to day situations at a company. I am therefore grateful to have done my master program at the University of Twente and have the help of some great and inspiring people.

Still, despite my own skills and experiences, I could not have finished this master thesis without the help of my supervisors at the University of Twente. I would, therefore, like to thank Matthieu van der Heijden and Leo van der Wegen for having the patience while supervising me during this research and giving a constant flow of positive feedback. And, furthermore, I would like to thank Dave van Diepen, who was my supervisor at Air Spiralo®, for helping me get the correct information and sharing his knowledge every day.

Alexander C. Krediet,
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Summary

This study focuses on the company Air Spiralo®, which is located in The Netherlands, Poland and Finland. The company is specialised in producing ventilation ducts and fittings for housing, utility and industry. The main production facility is located in Poland and operates according to the Make-to-Order strategy. As a result, the managers at the facility in The Netherlands have to make sure the production facility in Poland is manufacturing the right products as well as the correct quantities. Unfortunately, the managers at Air Spiralo® are not able to make a good tactical production plan since they currently only use the first three months of each demand forecast to calculate the production plan. As a result, the company has to cope often with insufficient labour capacity or high inventory levels as they are trying to follow the demand behaviour over the year.

Based on this problem description, two research goals were drafted. First, this study mainly aims to find a production planning model, which is able to plan production on a tactical planning level and also include preferences and requirements mentioned by the managers at Air Spiralo®. Second, this study aims to use the production planning model to find the optimal production plan for the year 2016 and give some recommendations about the use of workers and/or machines at the manufacturing facility in Poland.

To find the requirements for the production planning model, interviews were conducted with managers in The Netherlands and Poland. Based on these requirements, production planning models were searched for in literature that included some of the requirements. Then, the results from the literature review were used to set up the production planning model for Air Spiralo®. This production planning model was than validated with historical data, such as sales history, from 2015 and the manufacturing cost prices of individual products. Finally, the production planning model was used to find the optimal production plan for the year 2016. Here, the budgeted amount of worker FTE as well as the expected sickness and holiday leave for the year 2016 was used.

The main results of the first research goal are:

- An Aggregate Production Planning (APP) model was set up, which will search for the lowest possible total cost to meet a given demand forecast for a rolling horizon of 12 months.
- The total cost includes production hours of workers, both through regular time as well as overtime, and machinery. Furthermore, the total cost is also a summation of the holding costs for each period; which is dependent on the number of stored pallets.
- This holding cost is a result of storing items in two different storage locations. Because the cost rate for storing a pallet is different for these two locations, a piecewise linear holding cost function was included in the APP model.
- For each of the operation types, such as point welding or cutting metal sheets from a coil, in the manufacturing process, the required machine hours are calculated. These required machine hours can be used to analyse what the optimal use of machines are for the manufacturing flow lines.

The main results of the second and final research goal are:

- The optimal manufacturing strategy for Air Spiralo® is to follow the level strategy in which inventory is built up in periods of low demand to meet demand in periods where regular production capacity is insufficient.
- A brief sensitivity analysis showed us that the current holding cost of the regular warehouse is only allowed to increase at most 60% before the decisions of the APP model are changed significantly.
- We also found during the sensitivity analysis that the parameter value for overtime production is only allowed to decrease with 40% before the decisions of the APP model are changed significantly.
- It is profitable to lower the number of FTE in production from the current budgeted 80 to about 75. Total yearly cost will increase with about €7,000 because the APP model will have to plan production through overtime, but this is far less than the cost of having to pay five workers in production.
- It is interesting for Air Spiralo® to try and improve the productivity of workers in production. By improving productivity with only 2%, the objective value of the APP model decreases with €3,647. Moreover, such an improvement in productivity also means Air Spiralo® will also mean they will roughly need 2 production workers less. This, in the end, translates to a yearly cost saving of €23,647.

From the output of the APP model, we found quite a different production plan as is currently followed at Air Spiralo®. The APP model showed that it is best for Air Spiralo® to keep production level and build up capacity stock in periods of low demand in order to meet high demand in other periods. At the moment, the available inventory capacity at the manufacturing facility in Poland is not used for any capacity stock such as this. Therefore, the managers at Air Spiralo® have to try and implement such a manufacturing strategy at their manufacturing facility in Poland. Furthermore, the managers have to try and get familiar with the way the APP model uses. To help realise this, we have written a manual in which the purpose and usability of the APP model is briefly described. But also, this manual explains who should be made responsible for making sure the data is correct and accurate every time the APP model is run.

Furthermore, we advise the managers at Air Spiralo® to run the APP model every three months. By doing that, the advantages of planning on a tactical level are kept intact since they are not changing the production plan every month but only four times a year. Moreover, the first three months are always forecasted with enough accuracy. So, it is safe to not change the production plan for that period. Furthermore, we advise to managers to discuss internally the parameter values determined in this report. For example, the costs related to keeping inventory were estimated based on rules from theory and some rough numbers gathered during the research. The output of the APP model will only increase if more effort is put into determining the correct cost values for the holding cost function. And finally, we advise the managers at Air Spiralo® to try and include an upper bound on machine capacity for each operation type as well. Our analysis showed that the practical usefulness of the model would increase when the model is also restricted in planning machine capacity for each month. In that way, also machines can be planned according to the level strategy.

Contents

Chapter 1
Introduction

1.1 Company description

1.1.1 History

The company Air Spiralo® is specialised in producing ventilation ducts and fittings for housing, utility and industry. The company was founded in 1840. Back then, the core business was producing copper. After 1940, the company started producing central heating equipment and ventilation ducts next to their core business. Then, in 1992, the family De Haan took over Kennemer Schagen B.V., which is the part of Air Spiralo® that is located in The Netherlands, and changed the company's name to Kennemer Spiralo®. In 1993, the company opened their manufacturing facility Kentel in Poland at which their main production activities are currently situated. Since 2005, the whole company introduced the international company name Air Spiralo® and the core business was changed to the production of ventilation ducts and fittings. Finally, in the year 2008, a family company in Finland, which is highly specialised in manufacturing pressed fittings, was included in the Air Spiralo® group to manufacture a part of the product mix of Air Spiralo®.

1.1.2 Geographic orientation of Air Spiralo®

The company Air Spiralo® is a supplier for a broad range of customers, regarding both geographic dispersion as well as types. Their customers are located in, for example, The Netherlands, Belgium, Norway or England. And regarding customer types, Air Spiralo® supplies both wholesalers, such as Technische Unie in The Netherlands, as well as ventilation specialists. These different kinds of customers all supply a different kind of market, which results in a different kind of demand behaviour.

Furthermore, the company Air Spiralo® is divided up into several semi-decoupled companies. The company Kennemer Spiralo® is located in the Netherlands and is responsible for supplying and contacting the customers; therefore, the warehouse is also situated here. And, because this facility is mainly responsible for supplying the end-customers, the customer order decoupling point (CODP) is placed close to the end-product. And so, in order to be able to deliver the customer from on-hand inventory, this facility operates according to the make-to-stock (MTS) strategy.

The manufacturing facilities of Air Spiralo® are located in Poland and Finland. Because these facilities do not deliver their product to the end-customer, they operate according to a make-to-order (MTO) strategy. So, while these different facilities are all part of the same company, the manufacturing facilities are not directly involved with filling inventory levels, but simply produce what is asked of them. The manufacturing site in Poland is known as Kentel Polska Sp. z o.o. and holds the most number of employees; in total around 100. Through the rest of this thesis, we will refer to this facility as Kentel. At Kentel, the products are mostly manufactured manually. After production, the end-products are temporarily stored here. When a full truck can be loaded it will be sent in the afternoon towards the Netherlands, where it will arrive in the morning. The manufacturing site in Finland, known as Air Spiralo® Oy, is responsible for manufacturing semi-finished as well as end-products. These products are manufactured for a big part by automated machines. Just as the facility Kentel, this facility also operates according to the MTO strategy. The semi-finished products are, finally, finished at Kentel. At the moment, these semi-finished products are first transported to the Netherlands to make sure that the company is able to send full trucks to Kentel. The idea is to transport these semi-finished products from Air Spiralo® Oy to Kentel directly in the future.

Some parts of the finished-products are difficult to manufacture and require some more specialisation. These parts are, for example, fire dampers or motorised air regulators. Because the company does not want to be involved in manufacturing these products themselves, they purchase these products at other suppliers. All those parts will be sent to Kennemer Spiralo® first, where they distribute the necessary parts to Kentel. There, they assemble it to the finished products.

In the end, the total supply chain of Air Spiralo® could be shown graphically as follows. The dotted lines represent flow of information and the full lines represent physical flow of items.

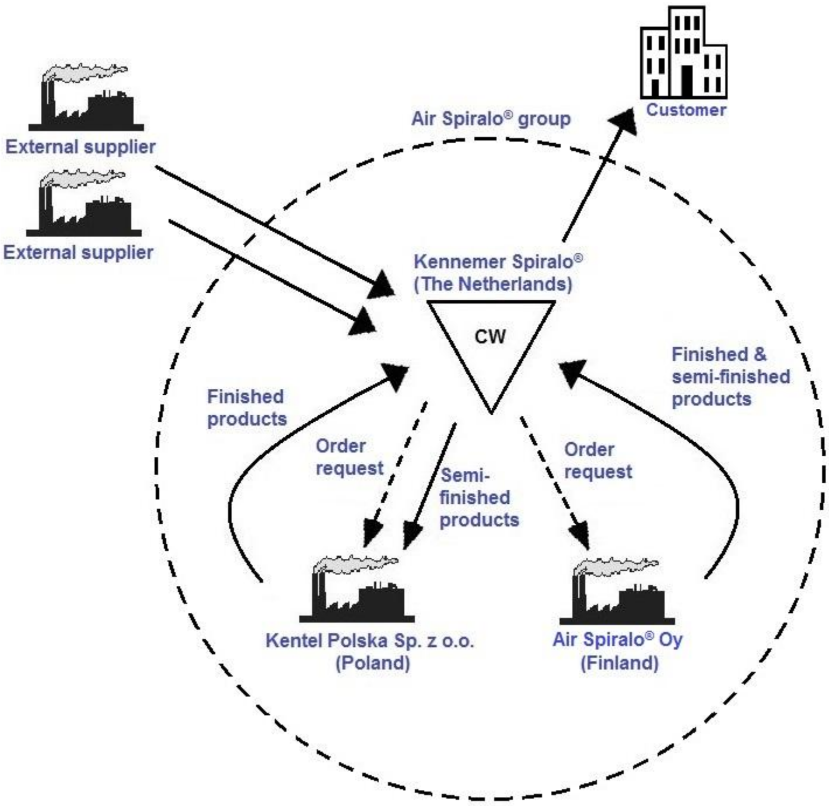

Figure 1 - Supply chain of Air Spiralo®

From this figure, it becomes clear that everything is managed from the location Kennemer Spiralo®. The production orders are sent from this location to the manufacturing facilities and also the customers are being supplied from this location.

1.1.3 Examples of projects and innovation

The products of Air Spiralo® can be found in some big projects in England. Some examples include the tennis club Wimbledon or the Gherkin building in London. Furthermore, Air Spiralo® is worldwide known for its high reliability of delivery and product quality. This product quality was established by inventing the so-called KEN-LOK® technology, which improves the air tightness of the ducts and fittings by including rubber seals in the edges of the products.

1.2 Motivation of the research

1.2.1 Problem description

By making sure that the customer receives the products as much as possible on the requested date, the company is able to distinguish itself from competitors. But, being able to deliver all demand as much on the requested date asks for a flexible manufacturing process or, otherwise, high inventory levels. Unfortunately, it takes quite some time to perform a set-up on a machine for producing a particular product. Therefore, the manufacturing facilities use batches in their production process to be able to manufacture more efficiently. This creates a mismatch between the goal of the company and reality. Adding to this problem, the number of available workers at Kentel cannot be changed easily; thus making production not very flexible. The reason for this is that it is difficult to find the rightly skilled workers and training them for the required operations takes quite some time. As a result, the company is also not able to increase the worker capacity in order to meet high demand.

Furthermore, as we briefly explained in Section 1.1.2, the manufacturing facilities operate according to the MTO strategy. As a result, these facilities can only react to the renewed production forecast that is provided by Kennemer Spiralo®. It is, therefore, the responsibility of Kennemer Spiralo® to make sure that the facilities in Poland and Finland keep producing the right amount of products necessary to fill the inventory levels. For example, if demand is significantly higher than expected, the re-order level is reached earlier. As a result, the inventory manager will send a renewed production forecast to the manufacturing facility earlier than the monthly update, as some sort of urgency order. And because the manufacturing facilities already have to sometimes cope with insufficient capacity, these urgency orders put a lot of pressure on this workers capacity at the manufacturing facilities.

Furthermore, the production forecast, and therefore the production planning, is currently done on a three-month basis. Only these three months can be forecasted with enough certainty by the company with the resources they currently have. For all the other months of the year, no prediction is done about expected production orders and related capacities. As a result, it is very difficult for the company to analyse the tactical strategies regarding their inventory and production.

And finally, the company is expecting sales to grow in the near future. A significant grow in sales would ask for some big changes, such as expansion of the warehouse or the manufacturing facility. But, because the managers do not analyse production forecasts on a tactical level, the managers have little information about the necessary machine or worker capacities.

1.2.2 Objective of the research

Based on this problem description, the best solution would be to set up an aggregate production planning (APP) model that is able to find the optimal production plan for the manufacturing facility Kentel for multiple months. This APP model will create the possibility, for example, to see the effects in inventory levels and capacities over a longer time period whenever a change in the sales forecast is made. Furthermore, this APP model can also be used to analyse the best manufacturing strategy for Kentel. From the problem description, it seems like the manufacturing facility Kentel has to adjust their worker capacities according to the production orders. But, as we have also mentioned, the workers capacity is actually fixed.

It will be interesting to see if the APP model finds it optimal to produce around the same number of items each month or that it is best to wait for an increase in demand.

Furthermore, the APP model will include multiple time periods and can, therefore, try to prevent major under- or overproduction by planning production over a longer period. As a result, instead of creating new schedules every time demand is significantly different from the forecast, only a small adjustment will have to be applied to this monthly schedule.

And finally, a major advantage of the APP model is that it can be made according to the wishes and requirements of the managers at Air Spiralo®. This allows us to build the model such that it reflects the situation at Air Spiralo® as much as possible. Only when it reflects the situation well, the output of the APP model will be most reliable.

1.2.3 Research questions

One of the important aspects in this research is that the APP model will have to be built according to the wishes and requirements of the managers at Air Spiralo®. For this, we will need to conduct interviews in order to discuss these wishes and requirements. Furthermore, data will have to be analysed to make sure that the correct information is used in the APP model. Relevant data could be the production costs per unit or number of available employees for production. And finally, the APP model will also have to be verified and validated to assure that the model represents the situation at Air Spiralo® as good as possible.

All these different tasks are based on a core research question. In this thesis, the following research question, which is based on the problem description, is formulated,

"*How could Air Spiralo® plan production and inventory over a longer planning horizon and decrease production nervousness in production as a result?*"

In order to find the answer to this research question, a few sub-questions will have to be answered. We will discuss the following sub-questions in this thesis, which are automatically converted into chapters.

<u>Chapter 2: Description of current production process and model preferences</u>

a. How are products manufactured at Kentel?
b. What information is used to calculate the inventory levels?
c. What information is included in the sales forecast?
d. How is the sales forecast translated into a purchase/production forecast?
e. What problems are present in the current way of working?
    i. Is seasonal demand an important aspect?
    ii. Is overtime production often necessary?
    iii. Is worker capacity always sufficient?
f. What are the wishes and requirements of Air Spiralo® regarding the APP model?

Chapter 3: Literature review

a. What is the purpose of an APP model according to literature?
b. Which kinds of APP or other production planning models have been developed in literature that incorporates the preferences of Air Spiralo®?

Chapter 4: Description of APP model for Air Spiralo®

a. How can we create an APP model for Air Spiralo® with the results from the literature review?
b. What are the parameters and decision variables of the model?
   i. What is the most suitable aggregation level?
   ii. What are the values for the different model parameters?

Chapter 5: Validating the APP model of Air Spiralo®

a. Is the APP model able to find the correct production cost from a given demand forecast?
b. Are the wishes and requirements, as given by the managers, modelled correctly in the APP model?
c. How sensitive is the APP model to the characteristics of the product group types?

Chapter 6: What does the APP model give as an optimal production plan?

a. What does the optimal production plan from the APP model look like for the year 2016?
b. What are the required capacities, regarding labour and machines, according to the APP model?
c. What is the best strategy for Air Spiralo to follow, i.e. chase, level or hybrid strategy?
d. On which aspects can Air Spiralo® improve with regard to production?

Chapter 7: Implementation of APP model at Air Spiralo®

a. How often should the APP model be evaluated?
b. What are the benefits of using the APP model?
c. Who should be made responsible for updating parts of the APP model?

1.2.4 Research approach

To find the answer to all of these sub-questions, we will need to have a good research approach. The first step will be to analyse the current method that is used for setting up a production plan according to the given sales forecast. This will mean that we will have to understand how a sales forecast is translated into a demand forecast per end-item. And also, we will have to understand what kind of inventory policy is used and how this policy determines when and how many products will have to be manufactured. Furthermore, we will investigate some of the problems that the company is currently facing as a result of the lack of fit between demand and production. At the end of this thesis, these problems can be analysed again to assess the improvements made by introducing the APP model. Then, the managers' wishes and requirements for an optimal production planning model will be described. These should be reflected in the APP model as much as possible.

After we understand the different process steps within the company, we will perform a literature review regarding APP and other production planning models. First, we will briefly explain the concepts of an APP model. After that, based on the wishes and requirements, we will perform a literature review to find relevant articles regarding APP and other production planning models.

Based on the results from the literature review, we will give a description of the theoretical APP model for Air Spiralo®. We will describe the design of the APP model and the information that is included in every part of the model. And along with this description, we will also explain how we have defined the different parameter values in the APP model. For example, one of the important aspects of the APP model is the choice of aggregation level. These choices will be based on an analysis of data at Air Spiralo®.

After that, we will perform some validation tests on the APP model such that we can assure the managers at Air Spiralo® the model reflects the situation at Kentel correctly. In one of these tests, we will analyse whether the same production costs are found from the output of the APP model as from the cost prices at Kentel. But, we will also investigate how sensitive the model is to any changes in parameter values of product group mixes.

Finally, after we have established that the model works correctly, we will let the APP model search for the optimal solution for the demand forecast of 2016. Furthermore, we will also investigate how much overproduction would be necessary according to the APP model with respect to the current situation. And finally, we will briefly give an indication of how the business processes are changed as a result of the APP model, along with a brief description of the implementation method.

1.3 Scope of research

For a model such as the APP model, it is important that the input is as good as possible. For every decision making model, the output can only be as good as the input. Besides the challenges in production planning, we have also seen that the company is struggling with demand forecasting. But, as we have mentioned in Section 1.2.1, the company is also not able to find the necessary capacities and production quantities from any given demand forecast. So, while it could be interesting to improve the forecasting methods, we will choose to focus on building an APP model such that the company can analyse the effects on the business from any demand forecast input.

Furthermore, we will start by planning production with the APP model only for the manufacturing facility Kentel. About 80% of all the products sold by Air Spiralo® are manufactured at Kentel. So, by doing this, a lot of the production planning challenges are already taken into account. Furthermore, the production layout at Kentel is bound to change in the near future. The managers want to produce the top 80% of production volume at Kentel via production flow lines; for which the CODP is pushed further away from the customer. The other 20% will be manufactured in a job shop layout; in which the production orders will be manufactured more or less according to the MTO manufacturing strategy. For this 80%, the process times in the APP model will reflect the actual process times best, because products flow easily to the next operation upon completion. In the job shop layout, products are manufactured in batches at each individual work centre. Upon completion, this batch has to wait for the next work centre to complete its previous batch. So, in reality, the structure times from the BOM will not reflect the actual manufacturing lead time of a product.

1.4 Outline of report

The remainder of the research is organised as follows. In Chapter 2 we will describe the current situation at Air Spiralo® for developing a production order for their manufacturing facilities. The literature review and discussion of management preferences concerning the production planning model will be given in Chapter 3. In Chapter 4 we will describe how the APP for Air Spiralo® is designed and which limitations are implemented. In Chapter 5, we will analyse whether the APP model works according to the wishes given by the management by performing some validation tests. Then in Chapter 6, we will analyse the output of the APP model with a demand forecast for the year 2016. Here, we will discuss how the company should try to realise this optimal production plan for 2016. Then in Chapter 7, we will briefly explain how the managers at Air Spiralo® should work with this APP model. Also, we will describe there who should be made responsible for updating parts of the APP model. Then finally, in Chapter 8, we will present the conclusions of this research as well as mention some recommendations regarding the APP model.

Chapter 2
Description of current situation

In Section 2.1, we will describe how the manufacturing facility Kentel is designed and how products, in a broad sense, are manufactured. Then, in Section 2.2, we will describe how Air Spiralo®, currently, manages its production planning process. By describing this process, we will understand what kind of information is available to implement in the APP model and, more importantly, what kind of information is missing. And furthermore, by describing this process step by step, we will probably come across some problems that are present at Air Spiralo®. We will discuss these problems in Section 2.3.And finally, in Section 2.4, we will end this chapter by describing the wishes and requirements, given by the managers at Air Spiralo®, regarding the APP model.

2.1 Manufacturing process at Kentel

As we have mentioned in the scope of this research, the APP model will only focus on the manufacturing facility Kentel. To understand how products are manufactured, we will briefly describe the manufacturing process in this section.

At the moment, the facility is mainly designed as a shop floor. This means that a specific manufacturing process, for instance the cutting process, is set up as a work centre in which multiple machines are available that can perform the process. After a product has gone through the process it is moved to the next cluster. If this cluster is already occupied, the product has to wait as work in progress (WIP).

The first stage is to cut 2D plates from a coil or sheet. This cutting can be done with a cutting knife or with a laser/plasma cutter. After cutting, these 2D plates are bent or rolled to create the 3D shape. Then, after the products are bent in the preferred shape, the 3D parts are welded together at the welding station. Here, the products are either point or line welded. Whether it can be welded on a machine mainly depends on the product type and the diameter. Large diameters are difficult to handle on machines because of their size. Therefore, those products are often manufactured by hand. One important aspect is that the number of required operations depends a lot on the product characteristics. For example, a silencer, from the CS product group, goes through the seaming process, while a duct coupling, from the SV product group, does not require this process. Furthermore, as mentioned in Section 1.1.2, some parts, such as motorised regulators, are purchased from external suppliers. If a product needs, for example, such a regulator, it is installed during one of the final stages.

After all the necessary processes have been performed, most of the products go through what is called the rolled over edge (ROE) process. This process has been introduced to create a Soft-Edge® onto the products. And with this Soft-Edge®, the products can also be fitted with the rubber seal, i.e. KEN-LOK® seal, to enhance the air tightness of the ventilation system. The addition of the Soft-Edge® has enhanced safety during installation dramatically. In the past, the products were simply sold with a sharp metal edge. As a result, the installer often cut himself on these sharp metal edges during instalment.

After the ROE process, the products are labelled and packed into boxes. Finally, after packing, the products can either be stored in the warehouse, where it will stay until a full truck load is ready, or made ready for shipment directly.

2.2 Production planning at Air Spiralo®

2.2.1 Inventory management

Because manufacturing and inventory levels are closely related, we will briefly describe the inventory policy currently applied at Air Spiralo®. A more detailed description of the inventory calculations can be found in Appendix B. As we briefly explained in Chapter 1, the company Kennemer Spiralo® is responsible for supplying the end-customer and, therefore, operates according to the MTS strategy. To maintain this MTS strategy, the company makes use of the (s, S)-inventory policy. This policy is applied to both the semi-finished as well as the finished products. The products with large diameters held as inventory consist of flat (semi-finished) sheets, which are later formed into an end-product.

The (s, S)-inventory policy means that the manufacturing decisions are based on a re-order level s and an order-up-to-level S. Furthermore, because the main goal of the company is to maintain the highest possible delivery reliability towards the customer and lead time demand is uncertain, the inventory manager has set a service level target. At the moment, the company has chosen to use the 'cycle service level' for their inventory model. The cycle service level states the probability of not stocking out in a replenishment cycle (Chopra & Meindl, 2007). Currently, a cycle service level of 94 percent is used to make sure they are able to deliver the customer from on-hand inventory.

To achieve this service level, the company makes use of a safety stock. This safety stock should account for the uncertainty in lead time demand. On top of this safety stock level, the re-order point s is placed. This re-order point s is placed such that the inventory level, on average, reaches the safety stock level upon delivery. So, this re-order point is equal to the safety stock level plus the average demand times the delivery time.

Then finally, the order-up-to-level S is calculated. When inventory reaches re-order point s, the order-up-to-level S determines how much should be ordered. For the situation at Air Spiralo®, this order-up-to-level S is calculated such that an integer number of pallets or boxes are ordered. This is to ensure the optimal use of truck capacity. Furthermore, the managers have stated an optimal replenishment frequency per product class. In total, three different product classes have been defined through the ABC classification. At Air Spiralo®, this ABC classification is based on the cost price and the yearly sales of the product. For product belonging to class A, the products are ordered on full pallets. For the class B and C products, orders are placed in units of full boxes.

2.2.2 The sales forecast

Every month a sales forecast, given as an Excel spreadsheet, is released by the sales department. This sales forecast is mostly based on monthly invoices and is, therefore, expressed in amount of Euros per customer per country and per month. The customers per country are further divided up into classes. For instance, the wholesalers are separated from the ventilation specialists. Furthermore, the sales forecast only includes the forecast for the current month and the next two months. With the information that the company can gather, these three months can be forecasted with enough certainty; other months are only included in the forecast for the total year.

A lot of information can be found in the sales forecast. But, for the purpose of this thesis, we will only describe the part that shows the forecast for the upcoming months. For each of these months a rolling forecast, commercial budget, financial budget and mathematical forecast is given. The rolling forecast is given by the sales department and shows how much the managers from the sales department think they can realise in the respective month or year. The financial budget, which is based on historical sales, states how much the company should be able to realise with full certainty for the respective month or year. The commercial budget is set as a target for the sales department to realise in the respective month or year. Finally, the mathematical forecast is calculated by multiplying the realised sales of that month by the number of workdays in that month and dividing it by the current workday number, thereby ending up with an expectation of the amount of realised sales for the current month. Finally, for the current month, the realised orders can be seen as well. The values for these realised orders, still given in Euros, are updated daily.

2.2.3 The production forecast

So, because the sales forecast is given in amount of Euros, the company does not know how much it has to produce of each individual end-product. To get this information, the sales forecast, described in the section above, is first translated into a sales forecast per country by summing up the forecasted sales for each customer in the respective country. This translated sales forecast, still expressed in Euros, is then forwarded to the inventory manager.

From this sales forecast, the inventory manager calculates a month-specific seasonal factor by comparing the sales forecast from the start of the year to the most recent sales forecast. A brief example can be found below.

Sales forecast given in January	August	September	October
TOTAL (%)	74,78%	106,27%	126,14%

Table 1 - Example of translating sales forecast into purchase forecast

Sales forecast given in July	August	September	October
TOTAL (%)	85,26%	103,7%	119,34%

Table 2 - Example of translating sales forecast into purchase forecast

In the first table, we can see how the sales forecasts for the months August up to October relate to a full year, i.e. a full year representing 1,200% (100% times 12 months). These values were estimated at the start of the year in January. The second table shows the sales forecast for the same three months at the start of July. Here, we can see, for example, that the sales forecast for August has increased with 10.48%. So, sales for that month has increased quite a bit but is still below average. If the inventory manager would, then, work with the average monthly sales as a sales forecast for August, he would overestimate the sales for August with 14.74%, i.e. the difference between 85.26% and 100%. So, to account for this change, the average historical sales for the individual end-product are multiplied with 85.26% for the month August. This means that the data from Table 1 is only used by the inventory manager to check how much demand has changed and whether this change is significantly different. Furthermore, these three months also show how much sales can differ between months. The month August is clearly a month in which sales is low and the month October is a month in which sales is high. Our APP model should be able to tackle such a difference by planning production quantities over a longer time horizon.

So in the end, the sales forecast given by the sales department is only used by the inventory manager to account for seasonal effects in the production forecast. If no deviation from the yearly sales forecast exists, the inventory manager will simply use the sales from recent 12 months as a sales forecast for that specific end-item in a full year.

With these forecasted sales quantities, the Excel spreadsheet checks whether the re-order point s is reached at any moment in the upcoming three months. If the re-order level is reached for any product, a production order is placed for that particular month.

Then finally, the determined production orders are shown per end-product per month for the next 3 months as a production forecast. Because the operational production planning is mainly left to the production managers of Kentel, this production forecast is also called a purchase forecast. Unless something drastically changes in the sales forecast, for example a new customer arrives, this production (or purchase) forecast is only recalculated every 2 months. This means that the third month in the production forecast only functions as an indication. This three-month overview is sent to Kentel, from which they will assess whether their current workers capacity will be sufficient. If they think they will be able to manufacture the forecasted amount, they will accept the production orders. And, unless the inventory manager changes the production forecast, this capacity check is not done for a whole month. Our APP model will improve this situation by analysing more than three months. First, the forecast for these three months will be inserted. Then, for all the other months in the planning horizon, we will use the more roughly demand forecast such that we can still show the seasonal trend over the planning horizon. By planning production over a longer horizon, we allow the managers at Kentel to anticipate on changes a lot better in the future.

2.3 Analysis of current problems

Now that we understand the different steps in the production planning, we can analyse some problems which are present at Air Spiralo®. These problems are discussed in the following sections.

2.3.1 Overtime production analysis

As we already mentioned in the introduction, the company has to cope with quite some overtime during the production process at Kentel. It is, therefore, interesting for us to analyse the use of overtime in recent periods. This could show us how important it is for the APP model to analyse whether overtime is actually the cheapest option.

In the figure below, the amount of overtime, expressed in full time equivalent (FTE), from January until October in year 2015 is shown in red. The blue bars show how much workforce FTE is employed in total at Kentel. The other colours show how much of this available FTE is used as, for instance, warehouse workers or how many have reported sick in the respective month. The blue bars show us that the total available FTE has increased by about 30% over this year. The reason for this is that the managers have hired extra floor workers for production, because of expected sales increases in the near future.

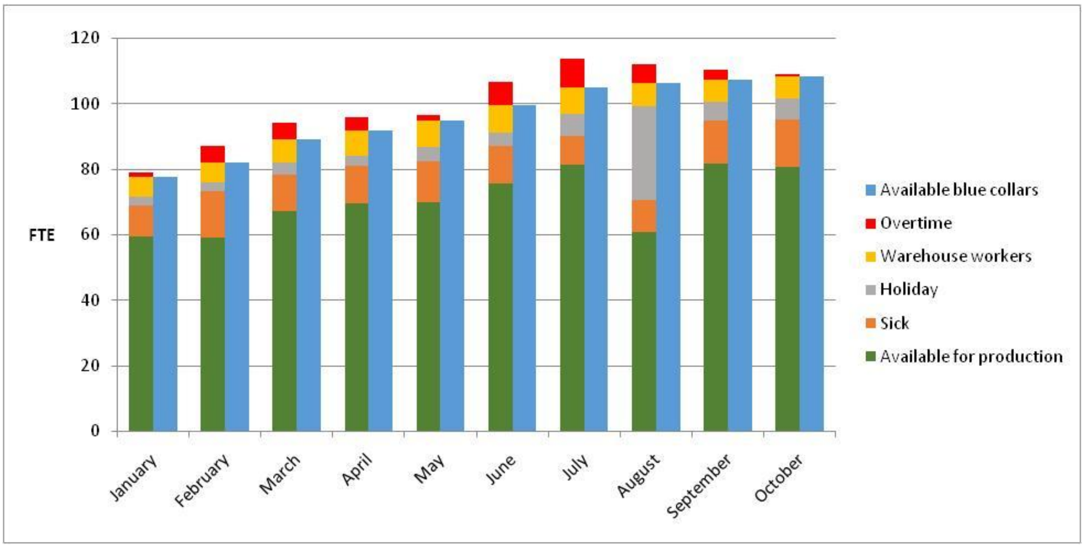

Figure 2 - Productivity at Kentel

We can also see, in the figure above, that overtime was necessary in every month. And the amount of overtime has been decreasing in the last couple of months. This decrease has been a result from the fact that the managers have noticed that overtime has been a dominant factor each month and have spent more attention to the causes of overtime. It will be interesting to see how much overtime the APP model will plan each month. At the moment, the managers have been trying to tackle overtime since they see it as something negative. But with the APP model output, we could see if overtime is really that negative. For example, it could be that it is actually cheaper to sometimes use overtime production instead of holding inventory for multiple periods. At the moment, the company is not able to analyse this.

One other remarkable point is that the amount of employees that have been reported as ‘sick’ is quite high. From Figure 2, we can see that about 10% of total FTE has been reported as sick in each month. Trying to reduce these numbers could have a major impact on the use of overtime. Unfortunately, we are not able to influence such a problem in this research. But this analysis shows it is a problem that the company should think about resolving.

2.3.2 Workforce capacity analysis

The APP model will optimise the production plan by, for some part, varying the planned production amounts in each period. If the APP model plans more production than the workers can do in regular time in a certain period, it automatically means that overtime hours are required. This, of course, is a result of not being able to outsource production at Kentel. It is therefore interesting to analyse how big the released production forecasts of recent periods were compared to the available workers capacity. This analysis can be found in the figure below. In this figure, we have plotted the available workforce FTE (green bars) against the amount of FTE required for production based on the production orders (red bars) in the months January up to October of the year 2015.

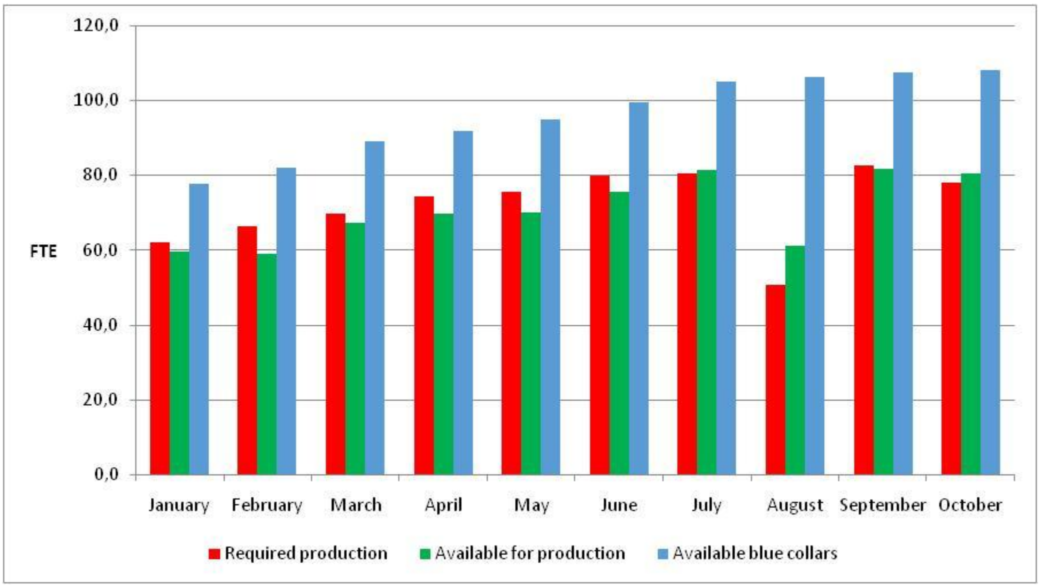

Figure 3 - Required production FTE against available workforce FTE

In this figure, we can see that for most months the amount of planned production has been demanding more than the available workforce FTE. Only in the months July and August enough worker-capacity was available. This could be a useful month to try and build up inventory for other periods. Furthermore, we can see that if we add, for example, the amount of FTE reported as 'sick', from Figure 2, to the 'available for production' here, the company would not have had any issues throughout these 10 months. This again shows that the amount of 'sick' employees is a critical problem at Kentel.

We have also plotted the total available blue collar FTE, shown in blue. The available blue collar FTE is the same data as used in Figure 2, when comparing it to the used overtime per month. Comparing the 'available blue collar' FTE to the 'required production' FTE, we can see that the company, actually, has enough workers employed. But, as we could also see in Figure 2, quite a lot of FTE is used for other purposes. As a result, the company has to deal with an insufficient available capacity for production. In our research, because we build a production planning model on a tactical level, we will not be able to directly change the productivity at Kentel. But, by analysing available capacity of each month with the APP model, we can try to attune production to the available workforce capacity better and, thereby, lower the differences we see in Figure 3.

2.3.3 Inventory levels at Kentel

During the planning horizon, the APP model can choose to hold items on stock. At Kentel, inventory is not so much necessary to reach, for example, service levels. But, it can be used in periods where regular production time is insufficient and overtime hours are a lot more expensive or not allowed. So, it actually acts as some kind of extra source of supply in times where regular capacity is insufficient.

To see how inventory is used at Kentel at the moment, we will analyse the inventory levels from the period 2014-2015. For simplicity, we have converted the unit of measurement from number of items into number of pallets. The reason for this is that, as we will discuss in Section 2.4.2, the inventories are bounded by the number of available pallet places in the warehouse. The inventory levels at Kentel, along with the upper bound on regular warehouse capacity, can be found in the figure below.

Figure 4 - Inventory levels at Kentel

In this figure, we have plotted two different boundaries for the inventory levels. In our APP model, these two boundary levels will be checked to see what holding cost rate should be applied. As long as the inventory levels stay below the orange line, the pallets still fit in the regular warehouse. The yellow line shows how much extra storage capacity is available at a different storage area at Kentel. For the pallets stored in this extra storage space, a different cost rate will be applied. Still, in total, the inventory levels may not exceed this yellow line because that is physically not possible. Furthermore, we have plotted the products from the RB product group separately as green bars. Because there is no space left in the warehouse of Kennemer Spiralo®, the managers have chosen to keep those items on stock at Kentel. On average, the inventory levels for the RB products is equal to 460 pallets, but in total 843 pallet places have been reserved for the storage of these products. Finally, the blue bars show us how much temporary inventory is used besides this RB inventory.

From this figure, we can see that the temporary inventory levels are quite high. At Kentel, products are, apart from the RB type, manufactured according to the MTO strategy. So, in theory, this temporary inventory should be zero in most cases. First, the big inventory increase in August 2015 is a result of the fact that required production is less than the available FTE. The cause of this can also be seen in Figure 3. There, the 'available for production' has been bigger than the 'required production' in the months July up to October. Because the company wants to keep producing items on a steady rate, i.e. not lay-off any workers, the company has been building up inventory in anticipation of future demand; even beyond the regular warehouse capacity. When demand increases again in the future, Kentel is able to deliver products from on-hand inventory and they will need less FTE for immediate production. This is something that our APP model will analyse as well. In the months where worker capacity is left over, the model will decide whether it is a good option to produce extra items which it will hold on stock. So, it will be interesting to see how the inventory levels from our model will look compared to this figure.

Still, we can see from Figure 4 that temporary inventory has been at least equal to 200 pallets in the last 12 months. Around the period of July 2015, the production process at Kentel was optimised and, as a result, the ordered products were often finished up to three or five days before shipment. This means that Kentel has about three to five full truck loads temporarily on stock each day. A full truck load (FTL) is equal to 99 pallets. So, three to five FTLs translate into inventory levels of 297 to 495 pallets. This effect can be clearly seen in Figure 4, from July 2015 the average inventory level increased from 250 pallets to 600 pallets per week. Still, this shows us that they keep about 100 pallets on stock beyond the items waiting for shipment. Again, it will be interesting to see if the APP model finds those numbers to be optimal as well during the planning period.

2.3.4 Analysing seasonal demand

An APP model is extremely useful for situations where seasonal effects come into play during the planning horizon. If these seasonal effects are present, an APP model should be able to tackle it by planning production optimal over a longer period. To analyse the seasonal effects at Air Spiralo®, we have plotted accumulated monthly demand of all products between the year 2013 and 2015 in the figure below. In this figure, the green line shows demand in the year 2013, the orange line shows demand in the year 2014 and, finally, the red line shows demand in the year 2015. For the company's sake, we have left out the values on the vertical axis.

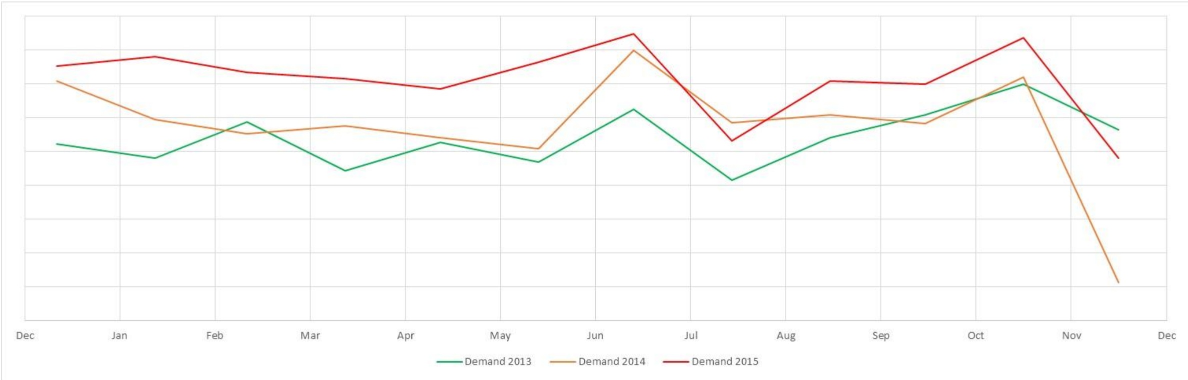

Figure 5 - Monthly demand for all products over 2013-2015

One thing that stands out immediately is the low demand around the month December. What happens is that the company is closed for two weeks around the turn of the year because of the Christmas holidays. Just before that period, we can see that demand increases in November. In that period, customers start to order more products to also fill their inventory levels as the calendar year closes.

Besides that, one other big seasonal effect we can derive from Figure 5, is the demand behaviour in the summer periods. Around the weeks of July, the construction holiday starts. In that period, construction comes to a hold and, therefore, demand for the products of Air Spiralo® decrease as a result. In previous years, the manufacturing facility Kentel was also closed in that period. The result of that can be clearly seen in the year 2013 and 2014 where demand decreases a lot around the month July. Furthermore, most of the workers at Kentel, as we saw in Figure 2, go on holiday as well. Therefore, not a lot of workers are available for production. But, as Figure 3 has shown us, the required production is still under the available capacity. As a result, these summer holidays could be a useful period in the APP model to plan extra production and build up inventories for other periods if that turns out to be the cheapest option.

Unfortunately, the counter effect of this construction holiday is that some companies are not closed during this period. The customers of those companies are not restricted by the construction holiday and keep ordering products. As a result, those companies have to order extra items to cover the period in which Air Spiralo® is closed. Besides that, construction is really thriving in the early months of the summer period, because of the weather conditions. So, demand in those periods also really increases. We can clearly see these effects in Figure 5, where demand first increases in June, before decreasing in July. This challenges our APP model as it will have to try and tackle such a peak demand with the little worker capacity that it is given.

2.3.5 Analysing demand behaviour of end-products

Besides the importance of seasonal effects during the planning horizon, it could also be beneficial to aggregate demand because of the high fluctuations in the individual end-product demand. By aggregating the products into product groups, we can see whether demand for similar products is actually a lot more stable and can be planned much easier. To see if it is beneficial to aggregate demand for products at Air Spiralo®, let us also analyse a few end-products which are manufactured at Kentel. We will first analyse the behaviour of monthly demand of a product which is one of the products sold most at Air Spiralo® in the figure below. Let us call this product A. The data is a collection from June 2011 up to September 2015. Again, we have left out the values on the vertical axis for the sake of the company.

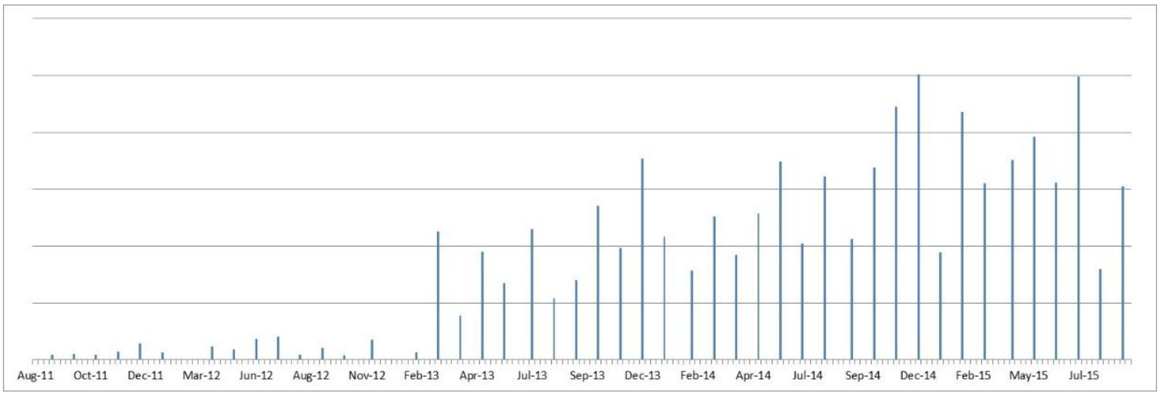

Figure 6 - Demand for product A (2011-2015)

What is interesting to see is that demand was very low around year 2011 and 2012. But a significant increase in demand can be seen around the start of 2013. What happened is that the sales manager started to convince customers to use KEN-LOK® products. This product is included with that technique and so a major increase in sales can be found from this figure. In Appendix A, we also show demand for the same product without the KEN-LOK® seal. This comparison clearly shows the effect of the change in demand. But still, while demand has increased significantly, we can also see that demand for this product is fluctuating quite a lot. So, it would be difficult to estimate the demand forecast with a lot of accuracy.

But, as we said earlier, this product A is actually the most popular product. Let us now focus on a product which is not so popular, but is still included in the MTS-strategy at Air Spiralo®. This second product, let us call it product B is not included with the KEN-LOK® seal. Within the demand market, products with the KEN-LOK® seal are becoming the standard, so a product like this one will probably be removed from the product mix in the near future. In the figure below, we have plotted monthly demand for this product B from the same period as product A.

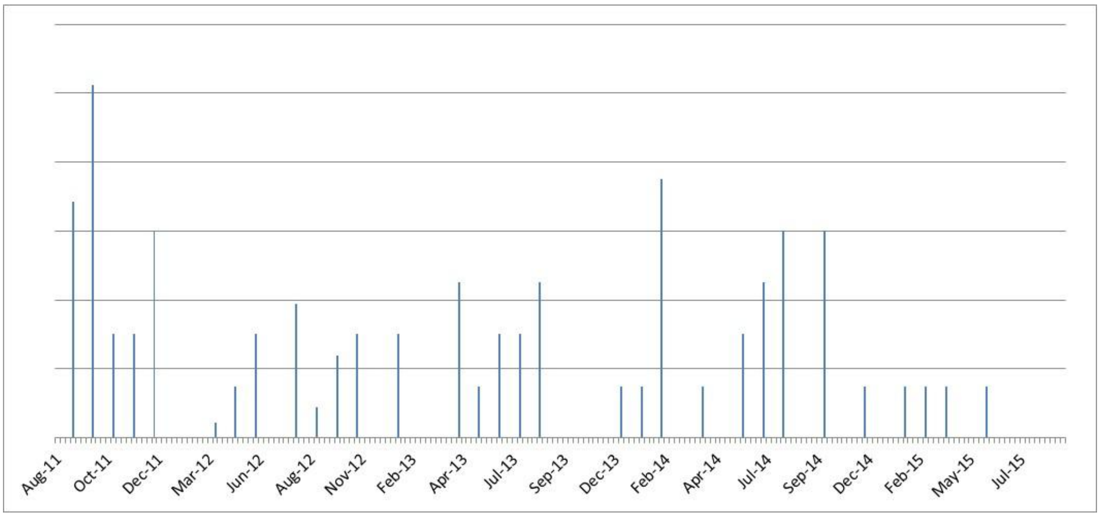

Figure 7 - Demand for product B (2011-2015)

In this figure, we can see that the demand behaviour is quite different from product A. Most of the customers have switched to products that are included with the KEN-LOK® seal. As a result, monthly demand of this product is zero quite often. Products like these have to deal with what is called intermittent demand. This means that demand arrives once every few months.

These two products already show us that it would be wise to set up an APP model to produce a monthly production forecast and analyse required capacities on an aggregated level. Predicting demand for the individual end-products can be very difficult and sensitive to errors. With the APP model, only accumulated demand forecast will be used; which is a lot less sensitive to changes on item level. And so, we will be able to set up a production plan that is a lot more robust.

2.4 Wishes and requirements for the APP model

To try and resolve some of these manufacturing problems via the APP model, we should make sure the APP model reflects the production process of Air Spiralo® as good as possible. Only then, the output of the model is most valuable for the company. Therefore, we will explain the different wishes and requirements for the APP model, which were mentioned by the managers at Air Spiralo® during interviews, in this section.

2.4.1 Planning horizon for APP model

The first thing that should be decided is the preferred length of the planning horizon in the APP model. The planning horizon should consider a pre-defined number of periods, often called time buckets, for which the demand forecast will be given. Since the APP model should consider production on a tactical level, time buckets for APP models are most often equal to months.

The managers mentioned that it would be helpful if the model is able to work with a rolling planning horizon of 12 months. In that case, the APP model can account for the seasonality, for example around the construction holidays, and look beyond the current three-month planning schedule.

2.4.2 Objectives of APP model

The most important aspect of the APP model is the objective function. From the objective function, the model knows what the criteria are for an optimal production plan according to the company.

The managers mentioned that the main goal of the planning model should be to find the lowest possible cost related to realising the forecasted production quantities at Kentel. The total cost should consist of labour and machine production, both by regular and overtime, and also holding cost.

The holding cost should hold two different cost factors. In case that inventory levels stay below the available regular warehouse capacity, the model should apply a pre-defined cost value for the regular warehouse. But as soon as the model plans inventory levels above this capacity, a slightly different cost factor should be applied, because the pallets have to be stored in an extra space. In that extra space, pallets cannot be stored as efficiently as in the regular warehouse and so the holding cost will be higher.

2.4.3 Constraints for APP model

Besides the objective function, the limitations or constraints for the planning model should be defined as well. These constraints should reflect all of the practical limitations present at the manufacturing process at Kentel. Only then, the APP model can search for the correct solution regarding production and inventories.

As we mentioned for the objective function, the inventory levels are allowed to rise above the regular warehouse capacity. The extra items held above the warehouse capacity will be charged with a different cost factor through a step function for the holding costs. Furthermore, the managers at Air Spiralo® mentioned that the APP model should consider the inventory levels as a way of capacity for production. As mentioned in Section 1.1.2, the manufacturing facility Kentel operates, mostly, according to a MTO strategy. Therefore, it does not use inventory such that it can meet demand from on-hand stock, but it can hold inventory for several periods such that less worker capacity is required in periods of high demand.

The second preference that became clear from interviews was that the company wants to have an overview of the required capacities for each machine type. The managers want to incorporate the different machine types into the model, because the company is thinking about re-configuring the production lay-out at their manufacturing facilities. It would, therefore, be very useful if the APP model is able to show how much capacity is necessary for each machine type. All these different product groups ask for different machine types. For instance, some products have to go through the seaming process, while others have to go through the ROE process. In total about 35 different process operations are in use at Kentel. We will have to analyse how many of these are required in the APP model.

One other requirement for the APP model is that the company does not want to allow the APP model to decide to hire or lay-off workers. The managers at Kentel mentioned that it is very difficult to hire new workers, because there are not a lot of qualified people available at the moment. It also takes a lot of time before a temporary worker can finally start working, because of all the legislations and trainings. The managers would, therefore, like to implement a hard constraint stating the available workforce in each month. The managers mentioned that, whenever regular production time is insufficient, the planning model should simply plan overtime production and not hire any extra personnel. By stating this as a hard constraint, we could analyse how much the total costs would decrease if this workers capacity is increased simply via a sensitivity analysis. In that case, the managers can choose for themselves whether it would be beneficial to hire an extra worker, based on this estimated cost decrease.

Furthermore, backlogging is something that the company does not want to allow in a tactical planning model. The company Air Spiralo® is widely known for its reliable delivery; this is how the company distinguishes itself from competitors. Whenever backlogging is created, it should be dealt with during operational planning. Therefore, we should implement a constraint that states that demand must be met at all cost in the specific period. And finally, subcontracting is not an option at Kentel. So again, whenever regular time production and inventory levels are insufficient, it automatically means that overtime production is required.

2.5 Summary

2.5.1 Production planning

In this chapter, we started off by describing how Air Spiralo® manages its organisation regarding production planning. From this description, we can state the following problems regarding production planning at Air Spiralo®,

- Inventory parameters are determined via formulas that have been adapted, based on experience, to the situation at Air Spiralo®; making them very error-sensitive.
- The analysis of productivity showed us that the company is coping with overtime of about 4 FTE on average. Through our APP model, we will analyse whether this is actually the cheapest option for manufacturing or whether it is better to hold items as inventory for some periods.
- The company has to deal quite often with insufficient worker capacity. Implementing the APP model should allow us to analyse the required worker capacity a lot better and act on it, if necessary, by planning overtime or temporarily holding inventory.
- Analysing total demand over the last three years has shown us that demand fluctuates quite a lot around the construction holidays. This will challenge the APP model to plan production optimal even in those periods.
- Demand behaviour can vary a lot between products. Some products are relatively easy to predict, while others are only sold a few months per year. Aggregating products and demand for the APP model should allow us to set up a more reliable production plan on a tactical level.

2.5.2 Wishes and requirements for APP model

In this chapter, we have also described the wishes and requirements, mentioned by the managers, for the APP model. In short, the following wishes and requirements were mentioned,

- The objective of the APP model should be to find the lowest possible total costs that are related to meeting the forecasted demand for Kentel. In the APP model, total costs will consist of production and inventory cost only.
- Inventory levels are allowed to rise above the available warehouse capacity. These extra inventory products will be charged with a higher cost factor. For this, we will have to define a piecewise linear function for holding cost.

- The APP model should be able to compute required capacities for different kind of machines types.
- Workers cannot be hired or laid-off. Insufficient capacity has to be compensated for via overtime production or holding inventory.
- Finally, subcontracting and backlogging should not be allowed in the APP model. Those options are only considered on operational level.

To see how we can include as many of these wishes and requirements in the APP model, we will have to perform a literature review regarding APP and other production planning models. We will describe this literature review in the next chapter.

Chapter 3
Literature review

In this chapter, we will first explain, in Section 3.1, what an APP model does and why it is used. After that, we will perform a literature review in Section 3.2 to try and find articles about APP and other production planning models which allow us to incorporate as many of the wishes and requirements that were mentioned in Chapter 2.

3.1 Aggregate production planning

In 1955, a new production planning model was introduced by the development of the linear decision rule model, also known as HMMS, by Holt and his colleagues (Holt, Modigliani, & Simon, 1955). The introduction of this model started the research and development of aggregate production planning (APP) models. An APP model deals with the process in which a company determines its ideal levels of capacity, production, subcontracting, inventory and stock outs over a specified time horizon for which a demand forecast is given by the use of a linear programming model. The way a linear programming model works is described in Appendix A.1. The planning horizon of an APP model usually consists of 3 to 18 months, but depends on the preferences of the decision maker. The demand forecast is usually based on a rolling horizon in which the forecast is moved forward dynamically.

The APP model is called an aggregate planning model, because it does not plan directly the stock-keeping units (SKUs), but the products on an aggregated level. This aggregation level must be chosen by the decision maker and can be chosen from several possible factors. Some examples of aggregation levels are weight, volume, process stage or process time of the products. For example, if we choose to aggregate products based on their process time, products with similar process times are aggregated into a product group (Chopra & Meindl, 2007).

The APP model finds the optimal solution by varying the decision. A decision variable can state, for example, the amount of planned production, in regular or overtime, of an aggregated product in a specific period. But, a decision variable can also state the inventory levels of the aggregated products at the end of each period. The objective function should reflect the requirements, given by the decision maker, of a good planning. It could be that the APP model should try to find the lowest possible workforce in each period necessary to meet demand, but it could also be that the total cost should be minimised over the whole planning horizon.

In order to find the ideal solution for the aggregate production plan, information is needed that defines the solution space in which the optimal solution exists. This information can consist of relevant costs, process times and/or capacity restrictions. Relevant costs could be production costs, such as labour and transport cost, or the costs for holding inventory. In case of capacity restrictions, one could think of the maximum available machine hours for production in a particular time period. But also restrictions concerning, for example, available overtime for production could be considered.

Finally, while the model searches for the best combination of the decision variable values, the APP model will choose a certain manufacturing strategy. If manufacturing and changing the workforce is relatively cheaper than holding many items as inventory, the model will perform a chase strategy. In that case, the model will adjust the production levels according to the demand in the corresponding time period by laying-off or hiring employees. But if holding inventory is actually cheap and hiring or firing workers is expensive, the model will choose to perform a level strategy. This means that the model will plan the same amount of production during low demand periods to build up inventory in anticipation of future demand. If neither of these strategies will resolve in the optimal value of the objective function, the model will perform a hybrid strategy. This means that the model will follow a mix of both strategies. For instance, the model will choose to only hire or lay-off a few number of employees. Beyond these few number of employees, it becomes too expensive to hire or lay-off workers and the model will perform a level strategy next to it.

3.2 Production models in literature

In this section, we will perform a literature review about APP and other production planning models that involve the wishes and requirements of Air Spiralo®, which we discussed in Section 2.4. If we are able to include as many of these wishes and requirements in our APP model, it will reflect the situation at Air Spiralo® as good as possible. And, as a result, the output of the APP model will be most useful for the company.

During this literature review, we will describe several different articles. In these articles, the researchers are free to define their own abbreviations for decision variables and parameters. As this will create a lot of confusion in our literature review as similar parameters or variables are denoted differently, we will also define our own abbreviations.

3.2.1 Single-objective-single-product APP model

The first requirement, mentioned in Section 2.4, was that we will only have to minimise the total costs regarding production and inventory. These aspects are well reflected by the APP model of Chopra and Meindl (2007). In this book, the researchers developed a basic APP model that aims to minimise the total costs, regarding production, inventory, backlogging and subcontracting costs for a single product(Chopra & Meindl, 2007).

Before the objective function can be formulated, the different decision variables and parameters of the model will have to be defined. In the APP model of Chopra and Meindl (2007), the following decision variables have been defined.

Decision variable	Description
$\boldsymbol{P_t}$	Number of items produced in period t [*units*]
$\boldsymbol{O_t}$	Amount of planned overtime in period t [*hours*]
$\boldsymbol{I_t}$	Number of items available in inventory at the end of period t [*units*]
$\boldsymbol{B_t}$	Number of units backlogged at the end of period t [*units*]
$\boldsymbol{C_t}$	Amount of production outsourced in period t [*units*]
$\boldsymbol{W_t}$	Workforce size in period t [*units*]
$\boldsymbol{H_t}$	Number of employees hired at beginning of period t [*units*]
$\boldsymbol{L_t}$	Number of employees laid off at beginning of period t [*units*]

Table 3 - Decision variables in APP model of Chopra and Meindl (2007)

The first decision variable P_t states how much is produced in period t. The second decision variable, O_t, states how many overtime hours have been used in period t. This variable is used when the inventory level at the start of the period, the regular time production and outsourcing capacities are insufficient. The third decision variable, I_t, keeps track of the inventory level at the end of period t. Through this decision variable, we can see whether the APP model has chosen to build up inventories in anticipation of future demand. The next decision variable, B_t, shows how much demand could not be met in period t. Those quantities are pushed to the next period and thereby added to the forecasted demand of the next period. Then, the decision variable C_t shows how much production is outsourced. So, if regular production time is insufficient, the APP model can choose to create a backlog, plan production in overtime or outsource it to an external producer. Then, in order to state how much regular production time is available, the decision variable W_t shows how big the workforce size is. This workforce size can be changed in each period t by hiring extra employees via the decision variable H_t or firing employees through the decision variable L_t.

Besides these decision variables, the APP model will have to know what the related costs of decision variables or other important factors are. Only then, the APP model can evaluate what the optimal decisions are throughout the planning horizon. These factors are defined via parameters. An overview of the parameters, defined by Chopra and Meindl (2007), can be found in the table below.

Parameters	Description
$\boldsymbol{t}$	Time units in planning horizon T [*months*]
$\boldsymbol{d_t}$	Forecasted demand in period t [*units*]
$\boldsymbol{clr}$	Production cost in regular time *[€/hour*]
$\boldsymbol{clo}$	Production cost in overtime [*€/hour*]
$\boldsymbol{c}$	Inventory holding cost per unit per period [*€/unit/month*]
$\boldsymbol{b}$	Backlogging cost per unit per period [*€/unit/month*]
$\boldsymbol{e}$	Outsourcing cost per unit [*€/unit*]
$\boldsymbol{f}$	Cost to lay off an employee [*€/worker*]
$\boldsymbol{k}$	Cost to hire an employee [*€/worker*]
$\boldsymbol{g}$	Material cost per unit [*€/unit*]
$\boldsymbol{r}$	Amount of items a worker can manufacture in regular time [*units/hour*]
$\boldsymbol{o}$	Amount of items a worker can manufacture in overtime [*units/hour*]
$\boldsymbol{q}$	Maximum overtime hours allowed per worker [*hours/worker*]

Table 4 - Parameters in APP model of Chopra and Meindl (2007)

The parameter d_t is given as input and states the forecasted demand in period t. For an APP model, it is assumed that this forecasted demand is deterministic throughout the planning horizon. The parameters clr and clo state how much one worker costs per hour by regular and overtime production respectively. The parameter c states how much it costs to keep one unit in stock for a whole month. Then, the parameter b states how much it costs to backlog one product into next period. This parameter could be a quantification of the damage to the image of the company by not being able to deliver the customer. Then, the parameter e states how much it cost to outsource a product. The parameters f and k state how much it, respectively, costs to lay-off or hire a worker. The parameter r states how many items a worker can manufacture by regular time. This quantity is based on the process time of the product. Next to this parameter, the parameter o states how much a worker can manufacture in overtime production. It could be that, because a worker is not as productive in overtime as in regular production time, this parameter differs significantly from the parameter r. Then finally, the parameter q states how many overtime hours are, maximally, allowed per worker each month.

With these parameters and decision variables, the objective function for the APP model can be formulated. This objective function of Chopra and Meindl (2007) minimises the total costs, regarding the related costs to all of the decision variables, over the planning horizon. The lowest cost will be found by varying the different decision variables for each period. In the end, the objective function is formulated as follows.

$$Min\ Z = \sum_{t=1}^{T} [clr \cdot W_t + clo \cdot O_t + c \cdot I_t + b \cdot B_t + e \cdot C_t + f \cdot L_t + k \cdot H_t + g \cdot P_t] \qquad (1)$$

The next step is to formulate the constraints, which defines the bounds of the solution space for the model. The researchers start off by formulating a constraint regarding the inventory level at the end of each period. This constraint is defined as follows.

$$I_{t-1} + P_t + C_t = d_t + B_{t-1} + I_t - B_t \qquad for\ \forall t \qquad (2)$$

Here it is stated that the inventory level of previous month plus production, either via own production or what is outsourced, should equal demand plus the backlog of the previous period. If too much production is planned, it can be stored as inventory by the decision variable I_t. And if too little is produced, a backlog is created via the decision variable B_t.

Furthermore, the APP model should be able to change the workforce size in each period. This is allowed through the following constraint.

$$W_t = W_{t-1} + H_t - L_t \qquad for\ \forall t \qquad (3)$$

In this constraint, the workforce size of period t is equal to the previous workforce size plus the amount of workers that have been hired in that period minus the amount of workers that have been laid off. Through this constraint, the model can choose to, for example, increase the production capacity by hiring extra workers.

After that, the model has to be forced to plan production in overtime whenever the capacity is still insufficient. To realise this, the decision variables stating the workforce size, the amount of production and overtime hours should be connected to each other. This is done through the following constraint.

$$P_t \leq r \cdot W_t + o \cdot O_t \qquad for\ \forall t \qquad (4)$$

Here it is stated that the amount which can be produced via regular time, given by $r \cdot W_t$, plus the amount which can be produced in overtime, given by $o \cdot O_t$, should give an upper bound to the amount of planned production in period t.

After that, an upper bound on the number of allowed overtime hours in each period is stated. For this, the following constraint is used.

$$O_t \leq q \cdot W_t \qquad for\ \forall t \qquad (5)$$

This constraint states that only q hours per worker may be done by overtime. This is to make sure that, if overtime hours turn out to be the cheapest option, the model does not plan all insufficient capacity through overtime production but also through the other decision variables, such as C_t.

Finally, since the objective function states that the decision variables should be minimised, it is important to state that the decision variables cannot be negative. Therefore, the final constraint is added as follows.

$$P_t, O_t, I_t, W_t, L_t, H_t, B_t, C_t \geq 0 \qquad for\ \forall t \qquad (6)$$

3.2.2 An FMS production planning model

The managers also mentioned that the APP model should, preferably, be able to work with multiple machine types and their respective capacities. To try and implement this wish, we will discuss the production planning model developed by Koltai & Stecke (2008). In this production planning model an optimal manufacturing schedule is created by analysing the different machine capacities of flexible manufacturing systems (FMS) (Koltai & Stecke, 2008). This production planning model only plans production for one time period. So, it is not the same as an APP model. But this planning model from literature is one of the few that incorporated machine types in a production planning problem the same way as was demanded by the managers of Air Spiralo®.

For this planning model, the researchers defined one decision variable and a few auxiliary variables. The definitions of these variables can be found in the table below.

Decision variable	Description
$\boldsymbol{X_n}$	Number of items produced of part type n
$\boldsymbol{PT_{hn}}$	Auxiliary variable stating the processing time of all operations of operation type h of product type n [*hours*]
$\boldsymbol{PS_{kn}}$	Auxiliary variable stating the processing time of all operations of operation type set k of product type n [*hours*]
$\boldsymbol{RT_h}$	Auxiliary variable stating the required capacity of operation type h [*hours*]
$\boldsymbol{RS_k}$	Auxiliary variable stating the required capacity of operation type set k [*hours*]

Table 5 - Decision variables regarding FMS model

With these decision and auxiliary variables, various parameters have been defined to calculate, amongst others, the machine capacities. The definitions of the parameters can be found in the table below.

Parameters	Description
$\boldsymbol{o_j}$	Operation j
$\boldsymbol{ot_h}$	Operation type h
$\boldsymbol{R_k}$	Specific combination of operation type k
$\boldsymbol{R_k^{''}}$	Set of operations that only contain the operation types belonging to R_k
$\boldsymbol{z_{km}}$	Specifies whether operation type *k* is assigned to machine m
$\boldsymbol{c_m}$	Capacity of machine m [*hours*]
$\boldsymbol{p_{nj}}$	Process time of part type *n* for operation j [*hours*]
$\boldsymbol{w_n}$	Weight value for part type n
$\boldsymbol{\beta}$	Maximum allowed over usage of machine capacity
$\boldsymbol{\alpha}$	Maximum allowed under usage of machine capacity

Table 6 - Parameters regarding FMS model

To explain the parameters from this table, we will use the example in Figure 8 below. The operation type o_j resembles, for instance, the ROE procedure in which the end-product is finished with a Soft-Edge®. Because this article discusses an FMS, each operation o_j could be performed by multiple machines. If such an operation o_j can be performed on a certain machine it is called an operation type ot_h, which we can see here below. Then, the parameter R_k denotes a combination of several operation types ot_h which are required to manufacture a certain item. In our example, this could be the process of performing ot_1 and

ot_2. A combination of such processes is called an operation set type k. And only if an operation set type k can be completed on a single machine, it is denoted as an R_k set.

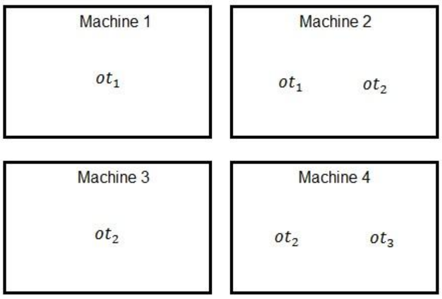

Figure 8 - Example of operation type sets

The binary parameter z_{km} makes sure that this parameter R_k is applied as required in the planning model. This means that whenever it is stated that operation set type k cannot be performed on machine m by R_k, the parameter z_{km} makes sure this does not happen in the model by stating a zero for the operation set k on that machine. In our figure above, it would mean that if a product requires the operation types ot_1 and ot_2, it can only be manufactured completely on machine 2. So, the binary variable z_{km}, regarding the operation set of ot_1 and ot_2, will only denote a 1 for machine number 2.

If a certain amount of available capacity for a machine is fixed, it is account for via the parameter c_m. The parameter p_{nj} states the process time of item type *n* for operation o_j. This parameter will be used to compute the required capacities on a machine later on. For this last parameter, it is assumed that the process time is not machine-dependent. So, it does not matter on which machine a certain operation is performed.

Then, the researchers define a weight parameter w_n, which will be used in the objective function to compute the objective function value. The value of this weight parameter mainly depends on what the decision maker wants to focus on. For example, if the focus is to maximise the sales revenues, the weight parameter w_n will be equal to the sales margin on each part type *n.*

And finally, the final two parameters, α and β, make it possible for the decision maker to allow some over or under usage on the machines regarding planned capacity. For example, by defining a value for the parameter α, the decision maker states that at least that amount of capacity should be used by all machines together.

So, in this model, only one decision variable is used in the objective function. As mentioned earlier, the focus of the objective function can be altered by defining a different value for the weight parameters w_n. In the end, the objective function is defined as follows.

$$Max\ Z = \sum_{n=1}^{N} w_n X_n \tag{7}$$

Here, the objective is simply stated to maximise the possible revenues from producing the products of type n.

Along with this objective function, some constraints are defined which compute the resulting capacities and restrict the model in stating the highest possible values for every X_n. The first constraint is defined as follows.

$$PT_{hn} = \sum_{\{j|o_j \in ot_h\}} p_{nj} \qquad for\ \forall h, n \qquad (8)$$

Here, the auxiliary variable, PT_{hn}, states how much processing time is used for a certain operation type ot_h. For example, for all the products which require the ROE procedure, their respective process times on a machine are summed up.

After this first constraint is evaluated for every operation type ot_h and part type n, the next constraint is defined as follows.

$$PS_{kn} = \sum_{\{h|ot_h \in R_k\}} PT_{hn} \qquad for\ \forall h, n \qquad (9)$$

Here, the auxiliary variable, PS_{kn}, states how much process time is required to manufacture one product for an operation type set *k*. To calculate this value, a summation is done over all the operations one product has to go through. So, for example, it is a summation of the rolling, line welding and ROE processes for a duct coupling (product group SV) at Kentel.

After the planning model has determined the optimal values for the decision variable X_n, the capacity requirements for an operation type ot_h can be evaluated. These values are evaluated via the formula below.

$$RT_h = \sum_{n=1}^{N} \sum_{\{j|o_j \in ot_h\}} p_{nj}\, X_n \qquad for\ \forall h \qquad (10)$$

In this formula, the process times for operation j of all parts n are multiplied with the production quantities X_n. The summation over both the number of parts and operation types, gives the overall required capacity for an operation type ot_h.

After having calculated the required capacities for a certain operation ot_h, the required capacity for an operation type set k can be evaluated as well. For this, the following formula is used.

$$RS_k = \sum_{\{h|ot_h \in R_k\}} RT_h \qquad for\ \forall h \qquad (11)$$

Here, the earlier evaluated value for the auxiliary variable RT_h are summed up, but only if the operation type ot_h belongs to the operation type set R_k. The result from this summation, gives the required capacity for an operation type set *k* through the auxiliary variable RS_k.

As we saw in Table 6, the researchers make use of a fixed machine capacity value through the parameter c_m. This machine capacity restricts the model to plan the highest possible production for every part n. To still allow the model to plan some extra production quantities if needed, a constraint is defined as follows.

$$(1+\beta) \cdot \sum_{k \in R_k} \sum_{m=1}^{M} c_m \cdot z_{k"m} \geq \sum_{n=1}^{N} X_n \cdot PS_{kn} \qquad for\ \forall k \qquad (12)$$

This formula first sums up all the machines that use a certain operation type set k. If operation type set k can be performed on any of the machines, the corresponding machine capacity is summed up for the upper bound on capacity on the left-hand side (LHS). On the right hand side (RHS), a summation is done over all planned production and the corresponding process time for the operation type set k. The parameter β states the maximum allowed over usage and should be defined by the decision maker. Through this RHS, the decision variable X_n is changed such that the summation stays within the allowed capacity.

Next to this allowed over usage of machine capacity, the researchers also stated a maximum allowed under usage of machine capacity. This could be useful if all of the machines should keep producing for at least a certain amount of time. The corresponding constraint is defined in the production planning model as follows.

$$(1-\alpha)\cdot\sum_{\{k'|R_{k'}\in R'_k\}}\sum_{m=1}^{M} c_m\cdot z_{k'm} \leq \sum_{n=1}^{N} X_n\cdot PS_{kn} \qquad for\ \forall k \qquad (13)$$

As we can see, this constraint almost does the same as equation (12). The only difference is that the sign and the LHS are slightly changed. Instead of stating an upper bound on the summation of the production quantities, it is now stated as a lower bound. And again, just as for the parameter β, the value of parameter α should be defined by the decision maker.

3.2.3 Piecewise linear cost function

One of the final wishes for the APP model is to include a cost function for the holding cost that changes depending on the inventory level. If the accumulated inventory level of all product groups rises above the capacity of the regular warehouse, a higher cost rate should be applied because the company will have to rent or temporarily create extra warehouse space. Unfortunately, no APP model exists in literature that discusses such a situation explicitly. Instead, we will discuss the article of Ertogral (2008) in which a piecewise linear cost function is used for the transportation cost to model a transportation and inventory decision making model (Ertogral, 2008).

The problem in this article is defined as follows. Several different kinds of items have to be ordered from a single supplier. Because the items are transported via trucks, it can be beneficial to sometimes order more than demanded for the respective period. Just as for an APP model, demand over the finite horizon is said to be deterministic. One downside is that ordering more items than the demand will result in inventory cost for the respective period. So, just as with our APP model, the model has to decide what the best choices are over the planning horizon.

Because the order costs depend on the order quantity in each period, the researcher defined a piecewise linear cost function for the transportation costs. This cost function can either be modelled according to the less-than-truck load (LTL) or the truck-load (TL) structure. In case of the LTL structure, the cost function is a linear increasing function with flat regions. For the TL structure, the cost function looks more like a step function or staircase function (Holmberg, 1994). Both cost structures are shown graphically in the figures below.

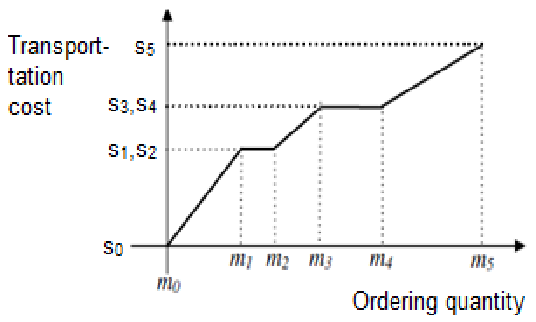

Figure 9 - LTL cost structure

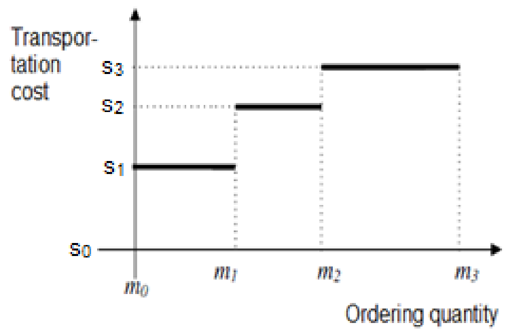

Figure 10 - TL cost structure

In Figure 9, we can see how the transportation cost increase as the ordering quantities increase. At some point, the transportation cost reaches a flat region. In this flat region, it could be that the supplier charges no extra cost for a certain amount of orders to encourage customers to order more products at the same time. But, after more items are ordered in a certain period, the transportation cost increase again because, for example, an extra truck has to be used. The other kind of cost structure is shown in Figure 10, here it does not matter how many items are ordered per truck. Only when an extra truck is required, the transportation cost increases. Because the size of trucks can differ, the difference between consecutive breakpoints m_l and m_{l+1} can differ as well.

In this article, the researcher has chosen to model the LTL cost structure of Figure 9, because it is the most general function to model. Just as for the other models discussed in this section, some decision variables and parameters are defined. We will first describe the parameters in the table below.

Parameter	Description
d_{nt}	Deterministic demand for item n in period t [*units*]
i_{n0}	Starting inventory level for product n [*units*]
k_n	Fixed order cost for item n [€]
h_n	Inventory holding cost of item n per unit per period [*€/unit/month*]
v_n	Weight per unit of item n
s_l	Transportation cost value at discount break point l [€]
m_l	Freight value of breakpoint l [*units*]

Table 7 - Parameters for inventory and transportation model

The parameter d_{nt} states the forecasted deterministic demand throughout the planning horizon. Then, the model uses parameter i_{n0}; which indicates how many items of type *n* are available from inventory in the first period. Then the parameter k_n states the fixed order cost, which should be paid if an order is placed. The parameter h_n states the costs for holding one item a complete period as inventory. The weight parameter v_n is used to compute the total order quantity OQ_t in period t. If this order quantity should be given as amount of kilos, the weight parameter v_n will denote the weight of item n. Then, the parameter s_l is the cost value at a breakpoint in the piecewise linear cost function. In this model, it states the total transport cost for a full truck. And, from this same piecewise linear cost function, the parameter m_l states the order quantity, or truck load, related to this s_l cost value.

With these parameters, we can now define the required variables in the decision making model. The description of each variable can be found in the table below.

Decision variable	Description
$\boldsymbol{X_{nt}}$	Amount of item *n* ordered in period t [*units*]
$\boldsymbol{I_{nt}}$	Inventory level of product *n* at the end of period t [*units*]
$\boldsymbol{OQ_t}$	Total number of items ordered (transported) in period t [*units*]
$\boldsymbol{Y_{l,t}}$	Binary variable indicating to which cost range (s_l, s_{l+1}) the accumulated order quantities OQ_t belong
$\boldsymbol{Z_{l,t}}$	Auxiliary variable denoting what fraction of each freight capacity breakpoint (m_l) is used in period t
$\boldsymbol{U_{n,t}}$	Binary variable indicating whether an order was placed for item *n* in period *t*

Table 8 - Decision variables for inventory and transportation model

The decision variable X_{nt} states the amount of items of type n that the model has chosen to order in period t. If this order quantity for type n was bigger than the demand for this type in period t, the remaining quantities are stored and added to the inventory level I_{nt} at the end of period t. Since the transportation cost is only dependent on the total amount of items ordered in a certain period, the decision variable OQ_t is used. To use the piecewise linear cost function, three extra decision variables are necessary. The reason for that is because the model would not be linear anymore after implementing a piecewise linear cost function directly into the objective function. The binary variable $Y_{l,t}$ indicates to which discount range the ordered quantities belongs. This means that $Y_{l,t}$ = 1 if $m_l \leq OQ_t < m_{l+1}$. The parameter l indicates the discount break point of the cost structure; the parameter m_l represents the order quantity of the breakpoint. The next variable, $Z_{l,t}$, is used to relate the ordering quantities OQ_t each period to the piecewise linear cost function. This auxiliary variable $Z_{l,t}$ can be a value between 0 and 1, and makes it possible to calculate the transportation cost each period as a linear extrapolation of two consecutive breakpoint cost values in the objective function. And finally, the binary variable $U_{n,t}$ states whether an order was placed in period *t* for item type $n.$ If no order was placed for any of the product types n in period t, the variable $U_{n,t}$ will be equal to zero and no order cost will be applied for period t.

With these decision variables and parameters, the objective function of the model can be formulated. In this article, the objective function minimises the inventory and transportation costs over the whole planning horizon. The formula for this objective function is formulated as follows.

$$Min\ Z = \sum_{t=1}^{T} \left[\sum_{n=1}^{N} (h_n I_{nt} + k_n U_{nt}) + \sum_{l=0}^{L} s_l Z_{lt} \right] \tag{14}$$

The first term within the brackets minimises the inventory holding cost and the fixed ordering cost. Here, the decision variable U_{nt} makes sure that the fixed ordering costs are only incurred when an order was placed in the respective period for product $n.$ The second term within the brackets relates to the piecewise linear cost function for transportation.

This objective function should, of course, follow the constraints such that it cannot create infeasible solutions. In the planning model of Ertogral (2008), these constraints are defined as follows.

$$I_{nt} = I_{nt-1} + X_{nt} - d_{nt} \qquad for\ \forall n, t \qquad (15)$$

$$I_{n1} = i_{n0} + X_{n1} - d_{n1} \qquad for\ \forall n \qquad (16)$$

$$X_{nt} \leq bigM \cdot U_{nt} \qquad for\ \forall n, t \qquad (17)$$

$$OQ_t = \sum_{n=1}^{N} v_n X_{nt} \qquad for\ \forall t \qquad (18)$$

$$OQ_t = \sum_{l=1}^{L} m_l Z_{lt} \qquad for\ \forall t \qquad (19)$$

$$Z_{0t} \leq Y_{0t} \qquad for\ \forall\ t \qquad (20)$$

$$Z_{lt} \leq Y_{l-1,t} + Y_{lt} \qquad for\ \forall t, l = 1..L-1 \qquad (21)$$

$$Z_{Lt} \leq Y_{L-1,t} \qquad for\ \forall t \qquad (22)$$

$$\sum_{l=0}^{L} Z_{lt} = 1 \qquad for\ \forall t \qquad (23)$$

$$\sum_{l=0}^{L-1} Y_{lt} \leq 1 \qquad for\ \forall t \qquad (24)$$

$$X_{nt}, I_{nt}, OQ_t, Z_{lt} \geq 0 \qquad for\ \forall n, l, t \qquad (25)$$

$$Y_{lt}, U_{nt} \in \{0,1\} \qquad for\ \forall n, l, t \qquad (26)$$

The first two constraints keep track of the inventory level each period. In constraint (15), the forecasted demand d_{nt} is met either via the amount of ordered items X_{nt} or available inventory I_{nt-1}. For the first period, the forecasted demand can also be met from available inventory, but this available inventory is stated via the parameter i_{n0}. Then, constraint (17) makes sure that the variable U_{nt} is changed to 1 whenever an order is placed for item n in period t. Here, the researcher has made use of the *bigM* method. A *bigM* is chosen such that the variable is forced to change in value in order to follow the other variable in the constraint (Griva, Nash, & Sofer, 2009). In this case, the variable U_{nt} should change to a 1 whenever something is ordered. The *bigM* is often equal to at least the highest possible value of, in this case, the X_{nt} variable. Constraint (22) computes the total number of items ordered in period t. Here, parameter v_n is used to convert the amount of ordered items into the required unit of measurement for the order costs.

The constraints (19) through (24) are related to the piecewise linear cost function. To explain the use of these constraints, we will refer to the cost structure in Figure 9. Let us assume that the accumulated order quantities OQ_t lies exactly between m_1 and m_2; where $m_1 = 500$ and $m_2 = 1000$. Then, with the result of equation (18), the auxiliary variables Z_{lt} compute what fractions of the breakpoint order quantities m_1 and m_2 make up the accumulated order quantity OQ_t in constraint (19). In our example, the resulting value for OQ_t is met exactly equal by stating $Z_{1t} = 0.5$ and $Z_{2t} = 0.5$. The other option would be to state $Z_{1t} = 0$ and $Z_{2t} = 0.75$, since that also results in a sum of 750, but that is not allowed by equation (23). The reason for the equal sign in constraint (23) is that it could be that the cost value s_2 is lower than s_1. Then, it would not model the cost function correctly by only using Z_{2t} in the objective function. So, with the values found for Z_{1t} and Z_{2t}, we only apply half of the cost of the breakpoint cost values s_1 and s_2 in the objective function. Then, to restrict the values of auxiliary variables Z_{lt}, the binary variable $Y_{l,t}$ is used in constraints (20) through (22). In our example, Z_{1t} and Z_{2t} should be larger than zero to make sure constraint (19) is met. Therefore, the binary variable Y_{1t} should be equal to 1 such that constraint (21) is met. This also allows the variable Z_{2t} to be larger than 0 through the same constraint. But, constraint (24) states that only one Y_{lt} is allowed to be 1. Therefore, the variable Z_{0t}, and all other Z_{lt}, cannot be larger than zero since Y_{2t} and Y_{3t} cannot be equal to 1.

Finally, the last two constraints allow the variables X_{nt}, I_{nt}, OQ_t and Z_{lt} to be continuous variables and restrict the variables Y_{lt} and U_{nt} to be binary.

3.3 Summary

In this chapter, we have performed a literature review to try and find articles regarding APP and other production planning models that discuss as many of the wishes and requirements given by the managers at Air Spiralo®. For a clear understanding, we have created a table in which we show which of the requirements were included in the respective planning model. These results can be found below.

Planning model	**Objective function regarding total cost**	**Computation of machine capacities**	**Stepwise linear cost function for holding cost**
Chopra & Meindl (2007)	X		
Koltai & Stecke (2008)	X	X	
Ertogral (2008)	X		X

Table 9 - Overview of planning models discussed from literature

Based on Table 9 and the literature review, we have concluded the following:

- We will use the model described by Chopra and Meindl (2007) as a basis for our APP model for Air Spiralo®. Their APP model includes the basic aspects of an APP model, which also reflects a lot of the situation at Kentel as well,
- The constraints regarding the different machine operations and capacities, given by Koltai and Stecke (2008), will be added to the APP model of Chopra and Meindl (2007). This allows us to analyse the required capacity for different operation types at Kentel,
- Finally, we will add parts from the model of Ertogral (2008) to the APP model of Chopra and Meindl (2007). This will allow us to model the piecewise linear holding cost function of Air Spiralo®.

The challenge is to combine these different models into one APP model. For example, the production planning model of Koltai and Stecke (2008) was not modelled as an APP model. Therefore, it is important that we understand how all of these different decision variables are used in the different constraints. Furthermore, the model of Chopra and Meindl (2007) only discussed one item type. In the APP model for Air Spiralo®, we should be able to incorporate multiple item types or product groups to implement the top 80% of production volume at Kentel. Furthermore, we will have to make sure that the separate objective functions are combined into a single objective. Only if we work with a single objective, we can use the APP model of Chopra and Meindl (2007) as a basis.

Combining these models will require us to make assumptions or leave out some parts. It is important that we describe these choices and therefore we will discuss and explain the design phase of our APP model for Air Spiralo® in the next chapter.

Chapter 4
Setting up the APP model for Air Spiralo®

In this chapter, we will first describe, in Section 4.1, how we will include the different wishes and requirements in our APP model by combining the production models found in the literature review from Chapter 3. Then, in Section 4.2, we will describe how the complete theoretical APP model for Air Spiralo® is designed. In Section 4.3, we will analyse what the best aggregation level is for setting up product groups as well as analyse and discuss the values of the different input parameters. Then finally, we will briefly describe the chosen spreadsheet solver in Excel for the APP model in Section 4.4.

4.1 APP model design phase

So, as we mentioned in the summary of Chapter 3, we have chosen to use the model of Chopra and Meindl (2007) as a basis for the APP model for Air Spiralo®. A few aspects of the other articles from literature will function as an addition to this APP model of Chopra and Meindl (2007). Combining these different models from literature cannot be done without some adjustments. Therefore, we will describe the whole design phase of the APP model in the sections below.

4.1.1 Basic APP model

To use the model of Chopra and Meindl (2007) as a basis for our APP model, we will have to make a few changes. First, we will change the definition of the decision variable O_t from 'the amount of overtime hours in period t' to 'the amount of planned production through overtime in period t. This allows us to let the model choose, if overtime is necessary, for which item type it is best to do so. The process time of each item type will be different. Therefore, it could be beneficial to plan overtime production for a certain item type. To allow this change in our APP model, we have to add the variable O_t to constraint (2) in which we match planned production, demand and inventory levels. Only then, the overtime production can also be used to meet the forecasted demand.

Unfortunately, the model of Chopra and Meindl (2007) did not allow for multiple item types; or product groups, as we will refer to it from now on. We have to add this dimension ourselves. To implement this, several constraints and decision variables have to be changed such that they can be included with the product group type dimension as well. To denote the product group type, we will use the dimension parameter $n.$ In case of the decision variables, we will add the dimension n to the amount of planned production, P_t , the amount of planned overtime production O_t and the inventory level I_t. And for the parameters, it is important that we can define the forecasted demand for each product group. Therefore, the parameter d_t will also be expanded with dimension $n.$

Furthermore, as we mentioned in Section 2.4, the company does not outsource production and also does not want to allow for backlogs on a tactical planning level. This means that we can exclude the decision variables B_t and C_t from our APP model. And more importantly, the APP model should not be allowed to make decisions regarding the workforce size at Kentel. It is difficult for the managers at Kentel to find the rightly skilled employees for production; those decisions are better left up to the managers. Therefore, we will also exclude the decision variables H_t and L_t. And, moreover, we will change the decision variable W_t to a parameter w_t; the available workforce size will be given as an upper bound on planned production in each month instead of a variable. The decision maker can state how much FTE is available for production each month, so this parameter w_t could still be different for each month. Then, because we still want the model to use overtime as soon as regular production time is insufficient, we will keep equation (4) in the model. And, because we have changed the definition of the decision variables O_{nt} and P_{nt}, we will have to change equation (4) such that we can use the new definitions. Parameter w_t will denote the regular worker capacity in hours. So, for equation (4), we have to make sure that every side of the constraint is given in units of hours. This can be done by multiplying the planned production quantities through regular time, P_{nt}, of product group n with the process times for the respective product group. Then, because we have changed the definition of the decision variable O_{nt}, we cannot use it anymore in equation (4). In constraint (4), we only want to restrict the variable P_{nt} with respect to the available worker capacity. The decision variable O_{nt} will be restricted in our model via equation (5). In that constraint, we also multiply the variable O_{nt} with the respective process time of product group n before we compare it to the available overtime hours. Only then, we can compare the amount of planned overtime production in hours to the allowed overtime production, which is also given in hours and is a result of multiplying the available regular production hours with a fractional value. This fractional value can be defined by the decision maker and indicates how many overtime hours are allowed per regular production hour.

Because we have changed w_t into a parameter, we will exclude it from the objective function. So, instead of multiplying parameter clr with the amount of workers w_t in the objective function, we will multiply clr with the amount of planned production in regular time P_{nt}. But, because the decision variable P_{nt} is given in numbers instead of hours in our APP model, this will create an imparity between the units of measurement. To solve this, we will multiply the variable P_{nt} also with the summation of the process times of required operations for product group n. The same goes for the clo parameter. We have changed the definition of the variable O_{nt} from the number of hours to the produced number of items in overtime. So, instead of multiplying it directly with O_{nt}, we also have to sum up the process times of the various operations and multiply it with O_{nt} to end up with the amount of overtime hours.

Furthermore, by changing w_t into a parameter, we also do not need the parameter r anymore. The amount of available workforce capacity is now simply given as a fixed value and does not have to be multiplied with the number of items one worker can manufacture per time unit. The same goes for parameter o. The amount of overtime production hours now results from the products groups planned in overtime and multiplying it with the respective process time.

4.1.2 Addition of machine types

From the model of Koltai and Stecke (2008), we will add the aspects regarding the machine types to our APP model to allow for the computation of the required machine capacities. The main focus of their model was to model FMS environments. Fortunately, this complexity is not necessary for Kentel. Each machine can only do one specific operation. Therefore, a parameter such as ot_h and the dimensions like m and k are not applicable to our model anymore. Whenever the model used a parameter with dimension m, we will simply state the parameter with dimension j, which relates to the operation type. And, because we do not have to check whether an operation type can be performed on the machine, we can also exclude the parameters R_k, $R_k^{''}$ and z_{km}. Because we exclude these parameters, we can leave out equations (8), (9) and (11).

One important issue at Kentel is that the amount of required machine time and worker labour for each operation type can be different. For example, in some cases, the machine is only assisting the worker in doing the operation. Or, otherwise, only a worker is required for a few operations. To make the distinction between the process time for operation j between the machine and worker clear, we will add the parameter pm_{nj}; denoting the required process time for operation *j* of product group *n* for a machine. We will still use parameter p_{nj}, but this parameter is now defined as the process time for operation *j* of product group *n* by a worker.

Furthermore, we have left out a few of their constraints to match the function of our APP model. The constraints we have left out were related to the machine capacities. Koltai and Stecke (2008) restricted the solution space with fixed under and over usage of available machine capacity. For Air Spiralo®, we want to use the APP model to analyse the optimal machine capacities. After the APP model has found the optimal solution, we will compare the required machine capacities to the current machine capacities at Kentel and discuss how and where improvements can be made. So, to allow the model to find the optimal machine capacities, we do not want to restrict it by stating lower and upper bounds. Therefore, we will not use the equations (12) and (13) in our APP model.

Now that we have added the parameter pm_{jn}, we also have to add a cost rate for machines as well, such that we are able to compute the total costs in our objective function. For this, we will add the parameter cm_j, which denotes the cost rate for operation type *j* by a machine.

4.1.3 Addition of piecewise linear holding cost function

In Section 2.4, we also mentioned that one of the wishes of the managers was to incorporate a holding cost function for which the cost value could change depending on the amount of items temporarily stored.

To implement this, we have chosen to use aspects from the model of Ergotral (2008). In his model, the transportation cost function was modelled as a piecewise linear cost function with different cost ranges. To define this cost function as a piecewise linear holding cost function, we will have to slightly change the definitions of a few variables. At Kentel, as more products are kept in storage, the holding cost function will increase linearly as a function of the number of stored pallets. At the first breakpoint m_1, where we reach the capacity of the regular warehouse, the cost rate for storing a pallet will change because pallets have to be stored in a different part of the building. For this part of the building, different cost aspects play a role. Also, for this extra warehouse capacity, an upper bound has to be stated. The sum of these capacities will give the value for the breakpoint m_2. We will explain later on, in Section 4.3, what the costs and storage values are related to the breakpoints m_1 and m_2.

For a better understanding of the holding cost function, a graphical representation of the piecewise linear inventory holding cost function at Kentel can be found below. Based on this description and Figure 11 below, our inventory holding cost function looks a lot like the LTL structure. Fortunately, this LTL structure was also modelled in the production model of Ergotral (2008). This allows us to use the same constraints in our model.

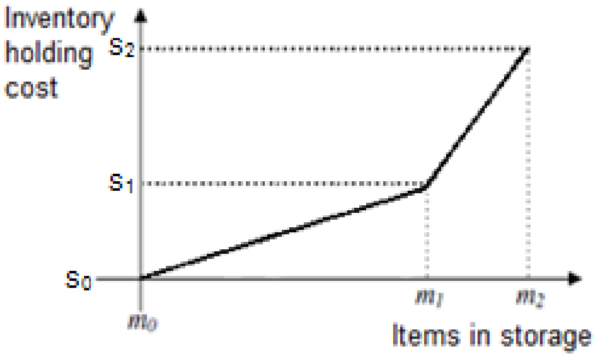

Figure 11 - Holding cost structure for Air Spiralo®

Our graphical representation of the holding cost function shows that, in contrast to the original LTL cost structure, we do not have a flat region. Moreover, our inventory cost function will not have a fixed cost aspect. So, if we do not use inventory in a period, the related costs are zero. As we will describe later on in Section 4.3, the holding costs will be derived from computing a monthly holding cost per pallet by looking at the yearly costs of the warehouse. As a result, the parameter k_n and decision variable U_{nt} are not necessary in our APP model. So, we will only use the last part of the objective function from Ergotral (2008) to model the inventory holding cost.

Because the inventory holding cost will also be dependent on the total number of pallets stored, we will still require equation (18) in our APP model. Only, instead of using the decision variable OQ_t, we will create a decision variable IT_t; stating the total inventory level at the end of period *t*. And to compute this IT_t, we will define v_t as the average number of pallets one item of product group *n* requires. This requires us also to change formula (19) in our model, such that the total inventory level is linked to the piecewise linear cost function. Here, in our APP model, the auxiliary variable Z_{lt} will state what fractions of the warehouse capacities m_0, m_1 and m_2 are used. And finally, because we will implement the piecewise linear cost function into the objective function, we can leave out the inventory cost aspect of Chopra and Meindl (2007) from the objective function. This cost aspect is now calculated via the auxiliary variable Z_{lt} and parameter s_l.

4.2 The APP model of Air Spiralo®

So, based on the choices and description from Section 4.1, we can now develop the complete theoretical APP model for Air Spiralo®. This theoretical APP model will be implemented in Excel; with which we will evaluate the optimal production plan over the given planning horizon.

First, we will describe the different parameters we will use in the APP model. The description of each parameter can be found in the table below.

Parameters	Description
d_{nt}	Forecasted demand for product group n in period *t* [*units*]
i_{n0}	Starting inventory level for product group n [*units*]
clr	Worker cost rate for regular production time [*€/hour*]
clo	Worker cost rate for overtime production [*€/hour*]
cm_j	Machine cost rate for performing operation j [*€/hour*]
q	Fractional value stating the allowed overtime per regular production hour
w_t	Available regular production capacity in period t [*hours*]
p_{nj}	Process time of a worker for product group n for operation type j [*hours/unit*]
pm_{nj}	Machine process time of product group n for operation type j [*hours/unit*]
v_n	Average number of required pallets in storage of product group type n [*pallets/unit*]
s_l	Inventory holding cost value at break point l [*€/month*]
m_l	Inventory capacity at breakpoint l in piecewise linear holding cost function [*pallets*]

Table 10 - Parameters of APP model for Air Spiralo®

Next, we will give the description of each of the decision variables in the APP model made for Air Spiralo®. These can be found in the table below.

Decision variable	Description
P_{nt}	Number of items produced through regular time of product group type n in period t [*units*]
O_{nt}	Number of items produced through overtime of product group type n in period t [*units*]
I_{nt}	Auxiliary variable stating the number of items available in inventory of product group type *n* at the end of period t [*units*]
IT_t	Auxiliary variable stating the total number of items stored in inventory at the end of period t [*pallets*]
$Y_{l,t}$	Binary variable indicating to which cost range (s_l, s_{l+1}) the accumulated inventory level IT_t belongs
$Z_{l,t}$	Auxiliary variable denoting what fraction of each inventory capacity breakpoint (m_l) is used in period t
RT_{jt}	Auxiliary variable denoting the required machine time for operation type j in period t [*hours*]

Table 11 - Decision variables of APP model for Air Spiralo®

Along with these decision variables, it is important that we define the parameters, which we will use in the APP model for Air Spiralo®. The definitions, along with their unit of measurement, of these parameters can be found in the table below.

These decision variables and parameters give us the following objective function for the APP model.

$$MinZ = \sum_{t=1}^{T}\left[clr \cdot \sum_{n=1}^{N}\sum_{j=1}^{J} p_{nj} \cdot P_{nt} + clo \cdot \sum_{n=1}^{N}\sum_{j=1}^{J} p_{nj} \cdot O_{nt} + \sum_{l=0}^{L} s_l \cdot Z_{lt} + \sum_{j=1}^{J} RT_{jt} \cdot cm_j\right] \quad (27)$$

In this objective function, the first two parts compute the costs related to the workers. First, the process time for a product group *n* is calculated by summing up over all operations. Then, the process time for all products groups is multiplied with the amount of items planned in regular time production, P_{nt}, and in overtime production, O_{nt}. The third part of the objective function computes the inventory holding cost. This will be evaluated through the piecewise linear cost function. Then, the final part of the objective function will compute the costs related to the machines. Here, we make use of the cost rate parameter cm_j and the auxiliary variable RT_{jt}. The auxiliary variable RT_{jt} follows from the planned production in each period, which can be seen in equation (32) below.

With this objective function, we will define the following constraints in our APP model for Air Spiralo®.

$$I_{n,t-1} + P_{nt} + O_{nt} = d_{nt} + I_{nt} \qquad for\ \forall\ n, t = 2 \ldots T \quad (28)$$

$$I_{n1} = i_{n0} + P_{n1} + O_{n1} - d_{n1} \qquad for\ \forall\ n \quad (29)$$

$$\sum_{n=1}^{N}\sum_{j=1}^{J} p_{nj} \cdot P_{nt} \le w_t \qquad for\ \forall t \quad (30)$$

$$\sum_{n=1}^{N}\sum_{j=1}^{J} p_{nj} \cdot O_{nt} \le q \cdot w_t \qquad for\ \forall t \quad (31)$$

$$RT_{jt} = \sum_{n=1}^{N} pm_{nj} \cdot (P_{nt} + O_{nt}) \qquad for\ \forall j, t \quad (32)$$

$$IT_t = \sum_{n=1}^{N} v_n I_{nt} \qquad for\ \forall t \quad (33)$$

$$IT_t = \sum_{l=0}^{L} m_l Z_{lt} \qquad for\ \forall t \quad (34)$$

$$Z_{0t} \le Y_{0t} \qquad for\ \forall\ t \quad (35)$$

$$Z_{lt} \le Y_{l-1,t} + Y_{lt} \qquad for\ \forall t, l = 1..L-1 \quad (36)$$

$$Z_{Lt} \le Y_{L-1,t} \qquad for\ \forall t \quad (37)$$

$$\sum_{l=0}^{L} Z_{lt} = 1 \qquad for\ \forall t \quad (38)$$

$$\sum_{l=0}^{L-1} Y_{lt} \leq 1 \qquad for\ \forall t \qquad (39)$$

$$P_{nt}, O_{nt}, I_{nt}, Z_{lt} \geq 0 \qquad for\ \forall n, t, l \qquad (40)$$

$$Y_{lt} \in \{0,1\} \qquad for\ \forall\ t, l = 0,1 \qquad (41)$$

In constraint (28), we have stated that forecasted demand should be met by planning production in regular-, overtime production or otherwise by having inventory available from the previous period. Then, constraint (29) makes it possible to compute the inventory level at the end of the first period. For this first period, we have defined a starting inventory for each product group as a fixed parameter. Then in constraint (30), we first sum up the planned production in regular time over the different product groups before we compare it to the available regular production time w_t. This constraint will state an upper bound on the allowed production quantities via regular production time each month. Then, constraint (31) has been adapted such that we can state an upper bound on the number of overtime production each month. Here, the value for q can be defined by the decision maker. Constraint (32) will be used to compute the required machine capacities in each period. Here, we sum up over all product groups and multiply the machine process time for operation j with the planned production quantities P_{nt} and O_{nt} of that product group. With constraint (33), we are able to convert the inventory levels from the number of items into the number of required pallets. This last part is important, because the holding costs at Air Spiralo® are defined per pallet. Finally, constraints (34) through (39) will allow us to model the piecewise linear holding cost function for Air Spiralo®. Here, we have not changed the equations as they were defined in literature. A complete description of these constraints can be found in Section 3.2.3.

4.3 Evaluation of data for APP model

Now that we know how we will design the model, it is important that we analyse what the input parameters will be for the model. These values should represent the situation at Kentel as much as possible. Only then, we can assure that the model will give a reliable output.

4.3.1 Choosing the product groups

The first important task is that we define product groups for our APP model. These products groups should consist of products that have similar process times and operation types. Only then, we can define a process time for the whole product group with which we can compute the necessary capacities and optimal production quantities over the planning horizon. Furthermore, it is important that these product groups are easy to understand for the managers at Air Spiralo®. Therefore, we will try to use the product groups as they are currently defined within the company as much as possible.

To assess the variation of process times within a product group, we use the coefficient of variation (CV). The CV value follows from dividing the standard deviation by the mean. If this value is lower than 0.40, the respective probability distribution could resemble a normal distribution[1]. For a normal distribution, the mode, which denotes the most frequent occurring

[1]See Chopra & Meindl (2007), p. 381

value in the sample, is equal to the mean. This allows us to use the mean process time as an appropriate representation of the product group characteristic in the APP model.

As we had mentioned in the scope of this research, the APP model will be focused on the manufacturing facility Kentel of the Air Spiralo® group. And more importantly, we will only include the top 80% of production quantities at Kentel, since these products will be manufactured across manufacturing flow lines instead of in the job shop. By only including these products, we have reduced the required number of product groups as follows. If we look at historical sales between January and October 2015, we can find, in total, 837 different products which were purchased from Kentel by Kennemer Spiralo®. If we only take into account the top 80% of production quantities, we only need to model 176 different products. The problem with these 176 products is that they are spread over 18 different products groups. And four of these products groups only consist of one product. Moreover, in the product groups RKDB and RKP, we came across a few products with significantly different process times. For the production lines, we want to include products that have similar process times such that the speed of the production line is not held back too much by the slowest product, i.e. the bottleneck product. We have therefore chosen to leave out the products from the RKDB and RKP product group as well as the products for which only one product was used in a product group. After excluding these products, the analysis shows us that we now need 189 products to cover 80% of production quantities again. After analysing the sales price of these 189 products, we have found that these 189 products already cover about 77% of total revenues for Kentel.

In the table below, we show to which of the product groups the 189 products belong. In the first column the abbreviation of the product group, which is mostly based on the Dutch expression, is shown. In the second column, we can see how many different products are included in the product group. This helps us to understand how big a product group. Finally, in the column, we can see the CV value for the average process time found for the product group type.

Product group	Product group size	CV
FLB	25	0.33
FLBF	5	0.14
GB	16	0.32
KL	32	0.34
PLB	11	0.37
RB	14	0.25
RKB	9	0.12
RKDB	5	0.30
RKP	4	0.19
RT_RTSPC	12	0.41
SV	30	0.73
SVH	12	0.57
ZSCB	14	0.12

Table 12 – CV value for the average process time per product group type

From Table 12, we can see that these 189 products are found in 13 different product groups. Of these 13 different product groups, we can safely use the average process time as a representation for 11 product groups. For those groups, the CV is close to the preferred value of 0.40.

For the product groups SV and SVH, we will have to split up the product groups such that the CV of those groups will fall below the 0.40 mark. After analysing the products and their respective process times in these two groups, we have found that the process times are diameter dependent. The best option was found to split the products around the diameter of 250 mm. So, the products with diameter lower than or equal to 250 mm are separated from the products with a diameter larger than 250 mm.

So, this means we will use in total 15 different product groups to model the 189 different products. Because many of the constraints in our APP model are product group dependent, those constraints will have a dimension length of at least 15.

4.3.2 Analysing the required operation types

Next, we also have to define different operation types for which we will compute the necessary machine and labour capacities. In case of worker capacity, we will have to check whether overtime production is necessary because we have insufficient production capacity. And in case of machinery, we will simply compute the necessary capacities for each operation type based on the model output and discuss whether that machine capacity is available.

As we briefly mentioned in Chapter 2, about 35 different operation types are possible for which a machine and worker is required. But, because we only take into account the top 80% of production volume, it could be that including all these operation types will not be necessary. So, just as we did for the analysis of required product groups, we will analyse whether some operation types can be left out. To be able to make this choice, we will analyse how many product groups, as chosen in Section 4.3.1, make use of a certain process operation type.

From analysing the 189 products, we have found that we do have to analyse all of the available process operation types. If we only include the operation types for which a machinery process time is stated by a product group, we are left with 24 different operation types.

Then, if we compare the average process time for an operation type between machines and workers, we find that workers also require a process time for the operation type ‘*sealing*’. So, if we would leave out that operation type, the accumulated process times per product group do not reflect the actual total process time for workers at Kentel. Therefore, we will also include this operation type in our APP model. This leaves us with a total number of required operation types of 25. For these 25 operations, we have analysed the respective cost rates of the machines. This cost rate will be used to compute the machinery costs from the resulting machine hours of the APP model in each month; this is also done in the cost price calculations at Air Spiralo®. So, by including the different cost rates for the machine operations, we make sure the total costs reflect the complete calculations for estimating production cost at Kentel. Finally, the cost rate for direct labour is not operation type dependent; that cost rate will be explained later on.

Finally, just as for the product group type, some of the constraints in our APP model are dependent on the operation type. These constraints are related to the required machine capacity for each operation type. Since we will model 25 different operation types, those constraints will have a dimension of 25. Furthermore, the process times are both product group as well as operation type dependent. We found that we will need 15 different product groups, so in the full APP model the process times have a dimension of 375. Fortunately, the individual process times are simply denoted as parameter values. Only the accumulated process time per product group will be used in the constraints; for that parameter the dimension is simply 15 again.

4.3.3 Analysing the process time per operation type

Now that we have determined which of the product groups and operation types are interesting to use in our APP model, it is important that we analyse the average process time per product group for each of those operation types.

To find these averages, we will make use of the Bill of Material (BOM) information of only the 189 products we found in Section 4.3.1. It is important that we only analyse the BOM from those products, because the rolling demand forecast for the APP model will be generated by selecting only these 189 products and accumulating the forecast for each product group. So, by computing the average process time per operation type with those products, we make sure the characteristics of the demand forecast correspond with the process time per product group type in our APP model.

To further make sure that the process times reflect the product group characteristics, we compute the average process time per operation type of each product group by using the yearly sales quantities of each individual product from 2015 as weighting factor. As a result, a product which is manufactured the most determines the average process time per operation type for the product group the most. Furthermore, if a process time for an operation type is not found within the BOM of a product, we will state a process time of zero. By doing this, the process time for an operation type which is not used by a lot of products within a product group will be really low. And this allows us to use this low average process time to apply it to any forecasted demand for the respective product group. If we would only calculate the weighted average process time for the products that actually use the operation type, we would define a total process time which does not reflect the average characteristics of one item from the product group. Finally, these computed average process time per product group type and operation type are loaded into the APP model

4.3.4 Holding cost

Next, it is also important for the APP model that we define the correct values for the breakpoint values in Figure 11 from section 4.1.3. This means we need the values for the costs of s_0, s_1 and s_2 as well as the number of pallet places related to m_0, m_1 and m_2. Only after we know these values, the APP model can decide if it is best to store items in the warehouse locations for a few periods or if it is cheaper to simply plan overtime production.

Let us first analyse how the pallet locations at Kentel are allocated to the different types of storages. For example, some of the available storage racks are used to store WIP items from production and others are used to store KANBAN items. So, this means that we could not use the complete warehouse as available for storing the capacity inventory in the APP model. We should only include the storage racks actually used to store finished products temporarily.

An overview of the allocated storages at Kentel, both for the regular warehouse and extra storage location, can be found in the table below. From this overview, we can choose the parameter values of m_1 and m_2. The value for m_0 as well as s_0 will be equal to zero, meaning that we do not charge any holding cost for an empty regular warehouse.

Storage facility	Storage type	Number of allocated pallets
Regular warehouse	**Full warehouse**	1578
	Work in progress	270
	Packing	84
	KANBAN items	54
	Storage of RB products	169
	Temporary storage truck loads	495
Total	**Available for capacity inventory**	506
Extra storage location	**Full warehouse**	1,302
	Storage of RB products	674
Total	**Available for capacity inventory**	628

Table 13 - Overview of allocated storage at Kentel

In this table, we can see that pallet places are reserved for the storage of RB products; both in the regular warehouse and extra storage location. The reason for this is that, as mentioned in Section 2.3.3, the RB products are only sent to Kennemer Spiralo® when an order arrives. In total, they have reserved 843 pallet places for storing these RB products; which translate into the figures found above for each of the storage locations. As we can see in the table, these RB products are mostly stored in the extra storage location. In that location, they do not use storage racks to store the pallets. The RB products are relatively light weighted. So, those products can be stacked easily without damaging the box or the product itself. So, this reservation of storage for RB products should not be confused with the inventory levels for the RB products in our APP model. In the APP model, the inventory levels are used as an extra capacity for production. It is not used to reach a service level, as is the case for this reservation of pallet places for RB products in the table above.

In the end, we can see from this table that the regular warehouse has, in total, 1578 available pallet places. From these 1578 pallets, 270 pallets are reserved for WIP items, 84 pallets reserved for the packing area and 54 pallet places reserved for the storage of KANBAN items. Furthermore, 20% of the RB products are stored in this warehouse, which takes up another 169 pallet places. And, as we also described in Section 2.3.3, we need to reserve about five truck loads of pallet places which are used to temporarily store the finished products waiting for shipment. So, in the end, this leaves us with a total of 506 pallet places on which we can store finished products in the regular warehouse. This number will be the value for m_1.

Then, for the other storage location, we can see that in total 1,302 pallets can be stored. Of these 1,302 available pallet places, 674 pallet places are used to store the RB products. Fortunately, no other types of storages are placed here. So, this leaves us with a total of 628 number of pallet places on which we can store finished products. As we have shown in Figure 10, the value for m_2 is equal to the sum of the capacity of the regular warehouse and the extra storage location. So, the value for m_2 is, in our case, equal to 1,134.

Next, it is important that we define the holding cost related to the values of m_1 and m_2, i.e. the parameters s_1 and s_2. This poses a challenge, because for the managers Air Spiralo® it is not really important how much it costs to store a certain number of items or pallets. As long as there is no big risk of storing that many items, they do not use some kind of variable holding cost function. The reason for this is that the warehouse is part of the production facility, which means they do not have to pay storage costs to an external party as more items are stored. Still, in our APP model, it is actually important that we define an incremental holding cost function. Only then, the APP model can search for the optimal inventory levels by looking at the total costs. So, in order to find the costs related to the breakpoints m_1 and m_2, we will make use of a method as proposed by Chopra and Meindl (2007). These researchers state that inventory holding cost is actually a percentage of the cost of the products. And that this holding cost is a result of five different cost aspects. For the situation at Kentel, two of these are most interesting. The other three cost aspects are negligible or not depending on the number of items stored.

The first aspect is the cost of capital. Cost of capital is, in essence, the costs related to a company's funds; both regarding debt and equity. At Air Spiralo®, equity is not so much in use. So, we will only make use of the cost of debt. The value for the cost of debt is often dependent on the market the company is in and so, the correct value was discussed with the financial department at Air Spiralo®. Then, this cost of debt should be applied to the cost of the products to end up with the first part of the holding cost. The cost of the products will be computed as following. We will use the cost prices at Kentel, including the material cost. And from those values, we will compute the average value of a pallet; given the list of products from Section 4.3.1. From this analysis, we have found that the average value of a pallet is equal to €244.29. This means that, when we want to fill all of the 506 pallets in the regular warehouse, a total value of €123,611 should be paid for manufacturing the products. When we take into account the cost of debt rate, the company has a cost loss of €4,450 to manufacture all of those products for storage. For the extra storage location, at which we had 628 pallet places available, this means we need a total of €153,414 to fill that location with full pallets. This translates to, based on the cost of debt, a cost loss of €5,523.

The second cost aspect for the holding cost is the occupancy cost. Occupancy cost denotes the costs related to the use of the location itself. So, this means we will have to look at the total housing cost at Kentel. At the moment, the total housing cost at Kentel is equal to €187,244 per year. These costs include, among others, the depreciation, insurance and energy used in a year. Next, we will generalise this housing cost to a cost parameter per square metre per month, such that we can calculate the related housing cost for each of the storage locations. The facility Kentel covers, in total, an area of 5350 m^2. So, based on this total housing cost, we find an average cost of €2.92 per m^2 per month. The regular warehouse covers a total area of 432 m^2; this includes the area where pallet racks are stored. So, the housing cost for this location is equal to €1,260 per month. On top of that, we have to add the depreciations of the pallet racks; these pallets racks are only found in the regular warehouse. So, the depreciation costs only affect the inventory cost in the regular warehouse. Based on the information from Air Spiralo®, we have found that the depreciation is equal to €37.15 per month for the 506 pallet places in the regular warehouse. We have to add this to the monthly cost of a fully utilised regular warehouse. Finally, the extra storage location covers a total area of 1460 m^2. So, for that location, the housing costs are equal to €4,259 per month.

So, in the end, we can state that the total cost for a fully utilised regular warehouse, the value for parameter s_1, is equal to €5,747 per month. For the extra storage location, we can state that the total cost for full storage is equal to €9,782. The major cost difference between the two storage locations comes from the fact that pallets are stored less efficiently in the extra storage location; therefore using much more floor space. So, finally, these two cost factors for the warehouse locations, give us a cost value of €15,529 for parameter s_2 in Figure 11 from section 4.1.3.

4.3.5 Available production capacity

One of the other important parameters in our APP model is the available worker capacity for regular time production as well as overtime production. For the available regular production time, we have defined the parameter w_t. This w_t is calculated as follows. First, the amount of available workers per month is stated in units of FTE. From these values, we subtract the number of workers that are on holiday, the number of workers expected to be sick as well as the number of service workers. This leaves us with the actual number of workers which are free to plan for production. These last three aspects can be stated based on historical values, such as the data we found in Section 2.3.1 while analysing the productivity, or can be inserted as predicted values for the upcoming months by the decision maker.

Then, we have to account for the fact that the APP model only models 80% of the production volume. If we simply use the structure times of each product included in the APP model and multiply it with its forecasted demand, we find that we only need about 65% of this resulting FTE available for production. Because this is quite dependent on the forecast of each individual product, let us state that we will only use 70% of available FTE for production. The remaining 30% will be used in the job shop, where they will manufacture the remaining 20% of production volume. The fact that we do not find that we need 80% of available FTE to produce the 80% of production volume is because many of the products in the remaining 20% have a significant higher process time than those in the top 80% of production volume.

Then, this resulting amount of FTE is multiplied with the amount of available working days of the respective month as well as with the number of working hours a worker is available per day. The decision maker can define a value for the productivity of a worker. This productivity value is related to the time spend to searching for tools and having breaks during the workday. So, if a worker is working 8 hours a day but actually has a productivity of 85%, we only multiply the amount of available FTE each month with a value of 6.8 as the amount of productive hours per day. At the moment, the managers have set a target for productivity of 85 percent. We will use this value in the APP model as well. In the end, this gives us the total amount of available working hours through regular production time as a function of the amount of FTE available for production per month.

Next, we should also state the maximum amount of available overtime production each month. By implementing such a value, we restrict the model in planning large amounts of production through overtime, which could violate any of the rules stated by the trade union. At the moment, a worker is only allowed to work 8 hours of overtime in a full week. So, on average, this translates to 1.14 hours per working day. This last value will be multiplied with the available working days and FTE in the respective month to end up with the maximum allowed overtime hours to be planned in that month.

4.3.6 Other input parameters

One of the other important aspects of the APP model is that we define the forecasted demand of each product groups for the rolling horizon of 12 months. We will compute this forecasted demand of a product group from the purchase forecast, which is calculated by the inventory manager. For all the end-products that make up a product group, we select the forecasted purchase quantities for each month. Then, the forecasted demand of a product group is computed by summing up the forecasted end-product demand for all products within the product group of each particular month.

We also define per product group the amount of pallets one item requires in the warehouse. This parameter value is computed by using information from the ERP system at Air Spiralo®. In this ERP system, it is stated how many products fit onto a pallet of a particular product. With all the products that make up a product group, we compute the weighted average of the number of items that fit on a pallet. Here, we will again use the yearly sales quantities as weight value per product. Finally, we will take the reciprocal of this average which will give us the number of pallets one item from a product group requires. These values will be used to convert the inventory levels from item quantities, which are a direct result of production quantities minus the forecasted demand quantities, to the number of required pallets. By knowing the required number of pallets, we can use the piecewise linear holding cost function to calculate the related inventory cost.

The value for the labour cost rate clr is extracted from the overviews in which the company determines the cost prices of products. From this overview, we have found that the cost rate for labour is equal to €5.86 per hour. Next, we also have to state how much it will cost if the model decides to plan production in overtime instead of through regular production. Based on interviews, the managers have mentioned that overtime is charged about 50% higher if it is done in regular day time and 100% higher if it is done in evening-hours or on weekend-days. At the moment, the production is planned in 2 shifts of 8 hours each. So, if overtime is needed it is often done during these evening-hours or, in extreme cases, during the weekend-days. This means we will choose to charge overtime 100% higher than regular production. So, the value for the labour cost rate clo is equal to the value of clr multiplied with a factor of two.

Finally, it is also important that we build an APP model in Excel which is easy to understand. Only then, it will be easy for the managers at Air Spiralo® to work with the model and analyse the results. For the design of our APP model in Excel, we have chosen to make use of an article written by Techawiboonwong & Yenradee (2002). For a detailed description of the APP model design in Excel, we advice the reader to read Appendix D. There, we have written a complete manual for the users of the APP model.

4.4 Use of Excel solver

So, as we have found in Section 4.3.1 and 4.3.2, we will create an APP model with decision variables of a dimension length of 180. For example, the planned production quantities are dependent on the time period (dimension 12) as well as the product group type (dimension 15). Unfortunately, the build-in Excel spreadsheet solver is not capable of dealing with that many dimensions. Instead, we will use a spreadsheet solver called OpenSolver which uses a Computational Infrastructure for Operations Research (COIN-OR) branch and cut (CBC) solver (Forrest & Lougee-Heimer, 2005). This solver works the same way as the built-in spreadsheet solver of Excel.

Finally, because we have implemented binary variables to model the piecewise linear holding cost function, we can no longer perform a sensitivity analysis on the values of parameters. Instead, we have to change the parameter values and analyse the effects on the APP model output ourselves.

4.5 Summary

In this chapter, we have described the theoretical as well as conceptual APP model design. Furthermore, we have also described the different choices we have made regarding the aggregation level as well as the parameter values. Based on these analyses, we can conclude the following for our APP model,

- In total, we will include 189 different products which are manufactured at Kentel in the APP model. These 189 products, which cover 80% of total production, will be spread over 15 different product groups.
- We will analyse in total 25 different operation types in our APP model. These have been selected from analysing which operation types the 189 different products use,
- We will need at most a dimension length of 180 for a few constraints and decision variables in our APP model.
- The holding cost for the regular warehouse location, therefore the value for parameter s_1, is equal to €5,747 per month for a total of 506 pallets. For the extra storage location, we have found a total holding cost of €9,782 per month for 628 pallets; this translates into a total value of €15,529 for parameter s_2 of the piecewise linear holding cost function.
- The model design in Excel will be based on the APP model of Techawiboonwong & Yenradee (2002). This allows for a step by step build up of the APP model.

Now that we have set up our conceptual APP model and the product groups along with their parameter values, we can validate our APP model by building the computerised model. With this computerised model, we have to make sure that it computes the correct cost values, based on a given demand forecast. Furthermore, we also have to make sure the APP model behaves as the managers at Air Spiralo® had asked us to. We will describe and discuss this validation process in the next chapter.

Chapter 5
Validation of APP model

Now that we have designed the conceptual APP model for Air Spiralo® in Chapter 4, it is important that we validate our APP model with a computerised model. To validate our APP model, we will make use of the complete APP model with all of the 15 required product groups and 25 operation types. Furthermore, we will discuss the validity with the help of some validation techniques as defined by Sargent (2013). In total, Sargent (2013) describes 15 different validation techniques. Some of these techniques are suited for validating graphical models and others for validating mathematical models. Since the APP model is not so much a graphical model, we will only discuss four of them in this chapter.

We will start off in Section 5.1 with a historical data validation in which we will compare the production cost output of the APP model to the cost prices of Kentel. Then, in Section 5.2, we will do an extreme condition test in which we analyse the behaviour of the piecewise linear holding cost function by setting extreme values for the parameters related to production and inventory capacity. Next, in Section 5.3, we will perform an operational graphics test. With that test, we will analyse the decisions of the APP model by comparing the cost calculations of choosing to keep inventory or to plan overtime production for a particular example. And finally, in Section 5.4, we will perform a sensitivity analysis regarding the CV value of the average process time per product group type for the APP model. As stated in Section 4.3.1, the CV value should be below 0.40 to use the average process time as a representation of the whole group. We will therefore analyse what happens to the output of the APP model when this requirement is not met.

5.1 Historical data validation

The first validation technique we will use is called historical data validation. With that technique, the output of the model is compared to the output of the actual system to see how accurate the model is. In our case, this means we will compare the cost output of the APP model to the output of the system at Air Spiralo®. More specifically, we will compare the production cost output of the APP model, when no overtime production and holding cost is required, to the cost estimated by the cost prices at Kentel. By performing this historical data validation, we test our choice of using the average process times per operation type, both for the worker and machine part, for each individual product group. If our choices regarding the product group types were incorrect, we will find that the cost output from the APP model differs a lot from the cost price calculations.

To make sure the APP model is not forced to use overtime production or inventory, we define the available production capacities such that the model has enough capacity to manufacture the forecasted demand each month through regular production time. Furthermore, we will start off with zero items on stock for every product group type such that the model is forced to meet all forecasted demand through production. As input for the APP model, we will use the demand forecast for each individual product from the year 2015. A description of how this forecasted demand is computed can be found in Section 4.3.

An overview of the costs from the APP model can be found in Appendix C. To analyse the accuracy of our APP model, a comparison of the different cost aspects from the APP model to the manufacturing cost prices at Air Spiralo® can be found in the table below.

Cost aspect	Cost output from APP model	Cost output from cost price Air Spiralo®	Difference
Labour	€394,446	€391,666	0.71%
Machinery	€219,571	€217,750	0.84%
Total	€614,017	€609,416	0.76%

Table 14 - Comparison of cost output APP model to system of Air Spiralo®

From this table, we can see that the APP model has found production cost, regarding labour and machinery, to be equal to €614,017. Using the manufacturing cost price of each individual product, we find total costs to be equal to €609,416. So, this cost output shows us that our APP model has an off-set of 0.76% with respect to the estimated production costs based on the cost prices at Kentel.

But, as we have explained earlier, this production cost is a result of summing up labour and machine costs. So, to further test this accuracy, we have also compared the direct labour and machinery costs separately to the respective parts of cost price calculations at Kentel. First, the direct labour costs, based on the cost price at Kentel, for manufacturing these products should be equal to €391,666. From Table 14, we can see that our APP test model has estimated direct labour costs to be €394,446. So, with respect to direct labour costs, our APP test model has estimated direct labour costs €2,780 (0.71%) too high. Next, the machine costs, based on the cost prices at Kentel, should be equal to €217,750. Again from Table 14, we can see that our APP model has estimated machine costs to be €219,571. So, regarding the machine cost aspect, our APP model has estimated the costs €1,822 (0.84%) too high.

Finally, the cost output is, for some part, related to the required production capacity. This means that a cost off-set of more than two percent on a given available FTE of about 80 would mean an off-set of more than 2 FTE. Therefore, the required cost off-set for the APP model was set to be at most two percent by the managers. So, with an off-set of only 0.76%, we can safely say that our APP model is capable of calculating the correct worker and machine costs based on the required capacities and demand forecast.

5.2 Extreme condition test

Besides testing the accuracy of the cost calculations, it is also important that the required behaviour of the APP model is modelled correctly. The best way to test a particular behaviour of a decision making model is to do an extreme condition test. In such a test, the model is forced to make choices in a certain way by setting extreme values for a few parameter values related to the behaviour tested. In our APP model, the most important behaviour is the use of the piecewise linear holding cost function. For this cost function, we have stated that the inventory levels are allowed to rise above the regular warehouse capacity. But for the items stored outside this regular warehouse, a different cost rate should be applied. We should analyse whether the APP model indeed uses different cost rates for the different storage locations, and more importantly, it first uses the regular warehouse space.

So, in order to perform this extreme condition test, we first have to set extreme values for the parameters of the APP model related to production and warehouse capacity. An overview of these values can be found in the table below.

Parameter	Value
Production capacity w_t	$6{,}000\ hours$
Overtime production cost clo	$10 \cdot clr$
Regular warehouse capacity m_1	$75\ pallets$
Accumulated warehouse capacity m_2	$175\ pallets$

Table 15 - Parameter values in extreme condition test

First, we will adjust the available production capacity. Based on the output of the APP model in Section 5.1, it would be interesting to see the optimal production plan when we state a fixed production capacity of 6,000 hours each month. With that many available regular production hours, the forecasted demand can be met with just regular production in seven of the 12 months. For the other five months, the APP model has to choose to hold inventory or plan overtime production. Next, we will set the cost rate for overtime production 10 times as high as for regular production, but the cost values for holding inventory will stay unchanged. By doing this, it will be more favourable for the APP model to hold inventory than to plan overtime production. Furthermore, we will still not use a starting inventory such that the APP model will have to meet the complete forecasted demand within the 12 months. And, because we also want to see how the APP model chooses to hold items above the regular warehouse capacity, we lower the parameter value for regular warehouse capacity to only 75 pallets; the extra warehouse space is limited to another 100 pallets.

Finally, an overview of the required pallet places through the planning horizon, after we let the APP model evaluate the optimal production plan, can be found in Table 16 below.

Period	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Warehouse space [pallets]	-	24.91	75.26	118.49	69.49	54.66	22.24	50.28	58.67	-	-	-

Table 16 - Overview of required inventory in extreme condition test

From this table, we can see that the model has planned to hold a total of 24.91 pallets in February. Based on our values defined for the warehouse capacities, these pallets still fit in the regular warehouse. Through constraints (34) up to (39) from Section 4.2, the APP model has found that the following should hold in order to meet the inventory level of 24.91 pallets: $Z_{0t} = 0.67$, $Z_{1t} = 0.33$ and $Z_{2t} = 0$. These values for Z_{lt} give us then a holding cost of €1,758.52 for the month February.

Next, the APP model used even higher inventory levels in April. All the products stored at the end of that month required a total of 118.49 pallets. That means that it has used the entire regular warehouse capacity of 75 pallets and another 43.49 pallet places of the extra warehouse. To connect the required pallet places to the piecewise linear holding cost function, the APP model has set $Z_{0t} = 0$, $Z_{1t} = 0.57$ and $Z_{2t} = 0.43$; showing that the APP model has used a fraction of the capacity from the extra storage location. These values for Z_{lt} result in a holding cost of €9,440.

So, this extreme condition test show us that the piecewise linear holding cost function is modelled correctly in our APP model. As soon as items are stored outside of the regular warehouse, the piecewise linear cost function makes sure that a different cost rate is used for those items. If the required inventory levels fit within the regular warehouse, the APP model makes sure that only a fraction of the total cost for the regular warehouse is applied.

5.3 Operational graphics test

Next, we also want to validate the decisions for any given situation in the APP model. As soon as regular production capacity is insufficient, our APP model is given two choices. It can choose to plan overtime production in the month where regular production capacity was insufficient or it could plan more production in earlier months and keep the products on stock until they are needed.

To test these decisions of the APP model, we will make use of the operational graphics test. In an operational graphical test, the values of a few performance measures are tracked to see if the model behaves as expected. In our case, this means we will analyse the costs related to holding inventory or planning overtime for a few situations in which regular production capacity was insufficient to meet demand and see if the decision made by the APP model was done correctly. Since the goal of the APP model is to find the lowest possible cost, the cheapest option should be chosen by the APP model.

To see how the model will behave when regular production time is insufficient, we again lower the available production hours to a fixed amount of 6,000 hours each month. The storage capacity for the regular warehouse is again stated to be equal to 506 pallets and the extra warehouse capacity is another 628 pallet places. Furthermore, we will use the same demand forecast from Section 5.1. Finally, overtime production is again charged 100% higher than regular production.

Next, let us pick out a certain situation from the output of the APP model. For example, the APP model has chosen to keep forecasted demand for the ZSCB product group in October on stock for a couple of months. In the months April up to October, no regular production capacity was left as it has used all of the 6,000 available hours to meet forecasted demand for each period. So, the model was given two choices to meet the forecasted demand in October. It could plan production through overtime in October or plan this forecasted demand through regular production in March and keep these items on stock until October. To really understand the results of these two choices, we have written out the cost calculations related to these two choices in the table below.

Available choices	Regular production in March	Holding cost (7 months)	Overtime production in October	Total cost
Keeping inventory	€2,758.43	€1,584.96	€-	€4,343.39
Planning overtime	€-	€-	€5,519.44	€5,519.44

Table 17 - Costs related to keeping inventory and planning overtime for the ZSCB product group

From this table, we can see that the model correctly chose to keep the forecasted demand on stock for the seven months instead of planning it through overtime in October itself. Keeping the items on stock required 21.28 pallets of the regular warehouse capacity. This translates into a holding cost of €226.42 per month. Although this holding cost has to be paid for seven months, it is still cheaper than producing it in October through overtime. So, with the given cost values for keeping inventory and planning overtime production, the first choice is the cheapest, and therefore optimal, option for the APP model.

So, this example clearly shows us that the APP model is capable of making the correct decisions for any given situation. As long as the warehouse capacity permits the extra storage of items and keeping those products on stock for a long period is the cheapest option, the APP model will choose that as the optimal solution.

5.4 Sensitivity Analysis

Finally, we will perform a sensitivity analysis. With a sensitivity analysis, the effect of changing the input or an internal parameter is tested. In our case, it will be most interesting to analyse how sensitive the APP model is to our choice of setting up the product group types by using the CV value of the average process time as a quality measurement. As discussed in Section 4.3.1, we had removed some products from certain product group types to end up with a CV value lower than 0.40. We stated that, only then, the average process time per operation type will reflect the actual situation at Kentel. So, to really test our choice of using the CV value as a quality measurement, it will be interesting to see what happens with the accuracy of the APP model output when we lower or increase the threshold value of 0.4 for the CV of the average process time a product group type.

To perform this sensitivity analysis, we will redo the historical data validation from Section 5.1. So, we will compare the production cost output of the APP model when it only plans regular production to the cost prices for each individual item. If the average process times do not reflect the characteristics of the product group type, we will probably see a significant difference between the cost estimates from the APP model and the cost price calculations.

The results of changing the threshold value for the CV for the average process time per product group type in the APP model can be found in the table below.

Threshold value for the CV	APP model off-set
0.30	0.05%
0.40	0.76%
0.50	0.93%
None	0.95%

Table 18 - Effect of CV on model accuracy

From this table, we can see the output of the APP model improves when we use a value of 0.30 as a criterion value for the CV value of the average process time. But, in order to use the APP model with such a CV value, we had to use another 2 product group types. The reason for that is that, with the criterion value of 0.30, one product group type did not meet our qualifications and had to be split up into three different product groups. Moreover, as we mentioned in Section 5.1, the managers at Air Spiralo® allowed an off-set of 2% for the APP model. So, having to work with even more product groups does not outweigh the fact that the output of the APP model is almost the same as for the individual products.

On the other hand, we can see from the table above that the accuracy of the APP model gets worse when we loosen our requirements for the CV value. For a CV value of 0.50, we were able to use a product group type less; which in return increased the off-set of the APP model to 0.93%. Furthermore, it is interesting to see that our APP model only differs 0.95% from the cost price calculations when we neglect the CV value at all. For one part, this is a result from the fact that we did not perform the complete analysis of selecting products for the APP model after changing the CV value. The CV value mainly requires us to set up more product groups for these 189 products. And so, the analysis in Table 18 is done with the same 189 products as analysed in Section 4.3.1. This means that we already had chosen products with, more or less, similar process times. If we would perform the complete analysis of using only products in the top 80% of production quantities at Kentel, we would find an off-set far above the 2% criteria.

Still, we would advise the managers at Air Spiralo® to use the CV value of 0.40. An advantage of using a higher CV value is that the decision maker is allowed to use the product group types as they are used at Air Spiralo®. But, from our analysis in Section 4.3.1, we found that this is actually not very practical for planning production over flow lines as process times will differ a lot and bottlenecks will be present. So, because the off-set of the APP model is within the given requirement of less than 2%, it is best to use the CV value of 0.40 as a criterion and keep the process times within a product group type within an allowed range. This increases the usefulness of the APP model output for production on operational planning level.

5.5 Summary

In this chapter, we have validated our APP model through several data validation techniques as posed by Sargent (2013). In total, we performed four different validation techniques. First, we performed a historical data validation technique in which we compared the cost output of the APP model to the cost price calculations at Kentel. Second, we performed an extreme condition test in which we tested the piecewise linear holding cost function. Third, we checked the decisions of the APP model with an operational graphics test. And finally, we performed a sensitivity analysis regarding the CV value of the average process time of each product group type. Based on these analyses, we have concluded the following.

- The APP model is capable of estimating the production cost for regular time production with enough accuracy. Based on interviews, the maximum allowed off-set was set to two percent. The results showed it only differs 0.76% with respect to production costs based on the cost prices at Kentel.
- The piecewise linear holding cost function works as requested by the managers at Air Spiralo®. Our analysis showed that the inventory levels are allowed to rise above the regular warehouse capacity by also storing items in an extra storage location. But, for the products stored in the extra storage location, a different holding cost rate is applied.
- The operational graphics test showed us that the APP model makes the correct decision based on the given objective function. If it is cheaper to hold a certain amount of items on stock for a couple of periods instead of planning it through overtime, the APP model will actually choose this cheaper option.
- From the sensitivity analysis we have found that it is sensible to use the CV value of 0.40. If the CV value is higher than 0.40, we cannot ensure the managers at Air Spiralo® the output of the APP model will make a lot of sense when the production plan is rolled into a production plan on operational level.

Now that we have established the APP model works correctly, we can start to analyse the optimal production plan for 2016 and compare it to the current situation at Kentel. Furthermore, we can try to analyse the cost improvements of changing, for example, labour capacities. This analysis of the complete model will be done in the next chapter.

Chapter 6
Analysing the 2016 scenario

Now that we have validated our APP model, we can let the APP model search for the optimal production plan for the year 2016 by using the demand forecast for that year. We will compare the required capacities from the APP model output to the current situation at Kentel to try and find some possible improvements. A description of this analysis can be found in Section 6.1. Next, in Section 6.2, we will analyse our choices regarding the cost values for overtime production and the cost value for a fully utilised regular warehouse. For this, we will vary the cost values and analyse when the behaviour of the model changes significantly. Finally, we will analyse in Section 6.3 what our APP model proposes as possible improvements of some parameter values.

6.1 Analysing production plan 2016

To test the APP model to its full potential, let us analyse the optimal production plan for the demand forecast of the year 2016. For the major part of that year, the production plan is still unknown. And so, it will be interesting to see what our APP model proposes as the optimal use of labour, machine and inventory capacities for each month. Furthermore, it will be interesting to see how much the APP model estimates the total cost to decrease if we would, for example, hire an extra worker or increase the available pallet places for finished products in the regular warehouse.

Next to the demand forecast for 2016, we should also state the available FTE for production for each month in 2016. At the moment, the managers at Kentel have estimated to use a fixed amount of 80 FTE each month production. These values are based on the calculated budget for the year 2016. As explained in Section 4.3.5, we subtract the expected sickness and holiday leave of each month to end up with the available FTE for production. Finally, we multiply the resulting amount of available FTE with the number of working days and shift hours each day to end up with the upper bound on regular production hours. Other than that, we use the parameter values as we determined in Section 4.3. Only now, we use the weighted average inventory level of every product group type at the start of the production plan.

To show the decisions of the APP model for the demand forecast for 2016, we have given an overview of planned production in Figure 12 below. Here, we have plotted planned production which was required to meet demand in the respective month as blue bars. The amount of planned production to increase inventory are plotted as orange bars. Finally, we have also plotted the available regular production hours of each month, which we denoted as parameter w_t, with a green line. As we mentioned in Section 4.3.5, this parameter w_t can fluctuate for each month because of the different amount of available working days in that month or the amount of expected sickness among the employees.

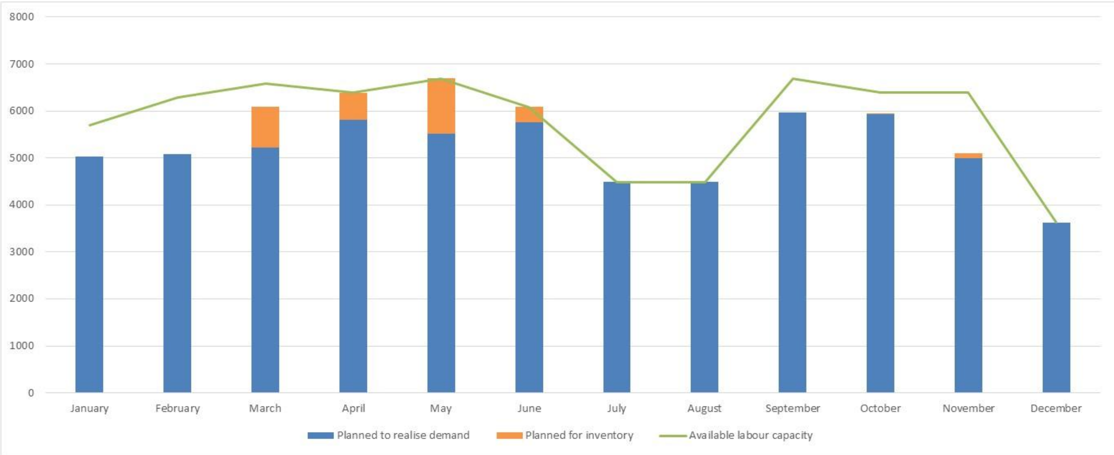

Figure 12 - Overview of planned production versus the available production in hours

From this figure, we can see the APP model has not planned any overtime production. The reason for that is that, with the available warehouse capacity and regular production hours, the APP model was able to meet the forecasted demand with the lowest possible cost. This shows us that the APP model is trying to minimise the use of overtime production. In Section 2.3.1, we saw that the managers have been trying to reduce the use of overtime production because they thought the use of overtime production was something negative. From the results of our APP model, we can now show the managers that this feeling was correct.

Furthermore, we can see from Figure 12 that the summer period is a difficult month for production planning. In that period, the amount of forecasted demand already requires all of the available production capacity. To compensate for this lack of available production capacity, the APP model has chosen to increase production in the months February until March such that inventory is created. As described in Section 2.2.3, the managers at Air Spiralo® currently make a production forecast on a three-month-basis. As a result, the managers are not capable of compensating for the summer period in January or February. So, this clearly shows the benefit of using the APP model. By planning production on a higher planning level, the managers at Kentel now know that they have to try and manufacture items in the early months of 2016 to keep them on stock for the summer period in which production capacity will be low.

Finally, we can conclude from Figure 12 that there is quite a bit of capacity left over. In 6 out of the total 12 months, we can see that the APP model has not planned production up to the green line. This could mean that it could be possible for Air Spiralo® to meet this demand forecast with less FTE. We will go further into detail about this in section 6.3.1.

6.1.1 Analysing the manufacturing strategy

One of our smaller goals for this research was that we wanted to analyse the optimal manufacturing strategy for Kentel. As mentioned in Section 3.1, this could either be a level, chase or hybrid strategy. Based on the problem description in Section 1.2.1, it seemed like the managers at Kentel want to work according to the level strategy such that they can keep a fixed worker level.

To be able to analyse this, we again use the results from Figure 12. From this figure, we saw that the periods between April and August are difficult for production planning. To see how the APP model has been able to resolve this problem, we have plotted the accumulated inventory levels in Figure 13. Here, we have also plotted the capacity of the regular warehouse with a red line. From that figure, we can see that the APP model has planned to build up inventory in the months March until May. As we can see in Figure 12, there is sufficient production capacity in the months leading up to May. Therefore, the APP model has used this production capacity to plan more production than necessary and build up inventory. After May, this inventory is used to meet demand in the months June until August and so inventory decreases again. Finally, because of the Christmas holidays, little production capacity is available in December. But, enough capacity was available in November. And so, a small bit of inventory is stored at the end of November to meet demand in December.

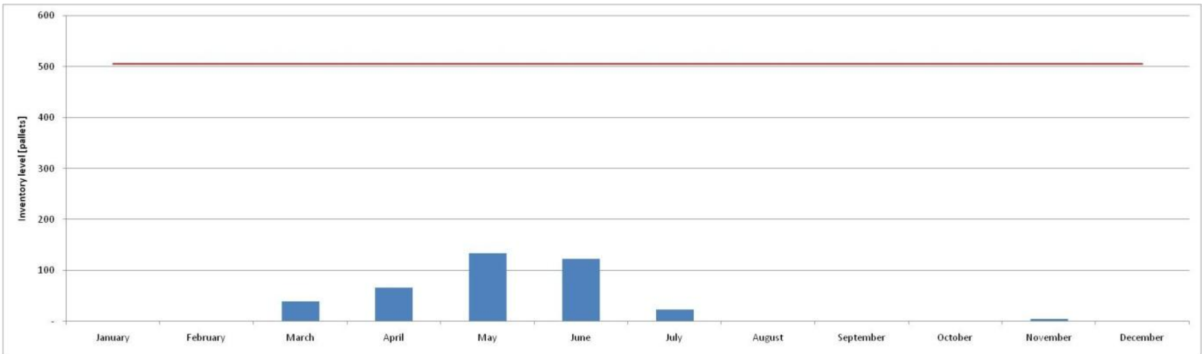

Figure 13 - Overview of planned inventory in APP model for 2016 scenario

So, this behaviour shows us that the APP model is performing a level strategy as much as possible. It rather plans extra production in months where capacity is sufficient, then to plan overtime production. This, of course, is a result of setting the available production capacity through the available FTE in 2016. For each month, the managers have stated that they will want to stay using a fixed amount of 80 FTE for production. Based on the estimated sickness and holiday, we are left with the available FTE for production. So, by stating this fixed 80 FTE for each month, we already state that we want the APP model to follow a level strategy. Still, we have allowed the APP to plan overtime production, so it could have chosen to perform a chase strategy in which it rather used overtime production instead of keeping items on stock. But, our APP model has not found that strategy to be optimal.

Finally, the results from Figure 13 show us that the APP model has not found in necessary to use the extra storage location. The planned inventory levels each period still fit within the regular warehouse. This shows that, by planning production on a higher level, the amount of required inventory could be planned such that only the regular warehouse is necessary for this capacity stock.

6.1.2 Analysing the optimal machine capacities

One of the other goals for the APP model was to be able to compute the required machine capacities in each month and discuss what the optimal use of machines is for this required capacity. Each product group type could represent a manufacturing flow line. Therefore, the output of the APP model could be used to determine the optimal use of machines along these flow lines. For this APP model, we have used a total of 15 product group types. This means that we have estimated that a total number of 15 flow lines have to be created at Kentel. It would not make a lot of sense for this research to discuss all of these flow lines. Therefore, we only discuss a few of them in this section.

The most interesting product group type is the RB group. The demand forecast for this product group type is quite high each month and so it will be interesting to see what the optimal number of machines would be for the different operation types required by the products from this product group type. To be able to analyse this, we have given an overview of the required machine hours per operation type for the RB product group type in the figure below.

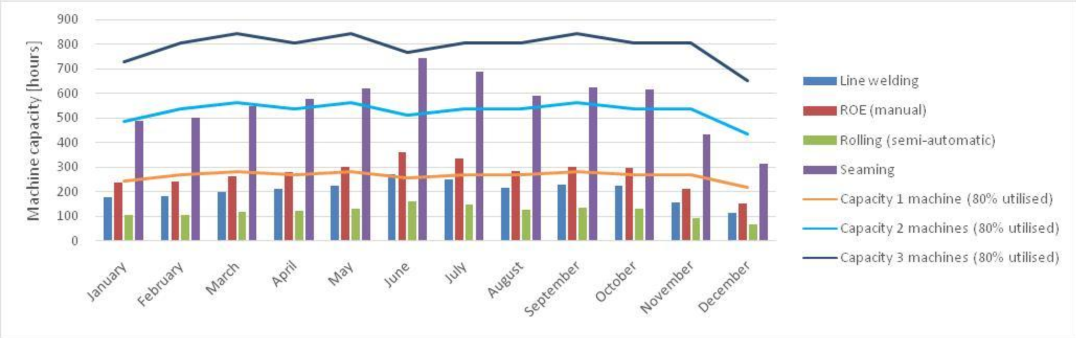

Figure 14 - Overview of required machine capacity for RB product group type

In this figure, we have also plotted the available capacity of one, two and three machines; which could be potentially be allocated to only the RB products. From literature, we know it is best to plan a machine only to 70 or 80 percent of its full available capacity, because the waiting time increases exponentially with the occupation (Lipsky, 2008). Therefore, we have only plotted the available machine hours for only 80% of its full capacity.

One interesting process operation type from this figure is the *Line welding* operation. For that operation type, we can see that the required machine hours are somewhere close to 80% of available machine capacity for one machine. So, based on these results, it would make sense to dedicate one machine completely to the operation type *Line welding* explicitly for the flow line with RB products.

On the other hand, we can see that the operation type *ROE (manual)* often requires more than 80% of capacity for one machine. Therefore, it would not make sense to dedicate only one machine to this operation type for the RB products. For this operation type, it could be beneficial to place a manufacturing flow line next to that of the RB product group type, such that the two manufacturing flow lines together would require about 80% of two machines for the *ROE (manual)* operation type.

To give an example for making such an analysis, we have plotted the required machine hours for the *ROE (manual)* operation type for the RB & PLB product group types together. An overview of this can be found in Figure 15 below.

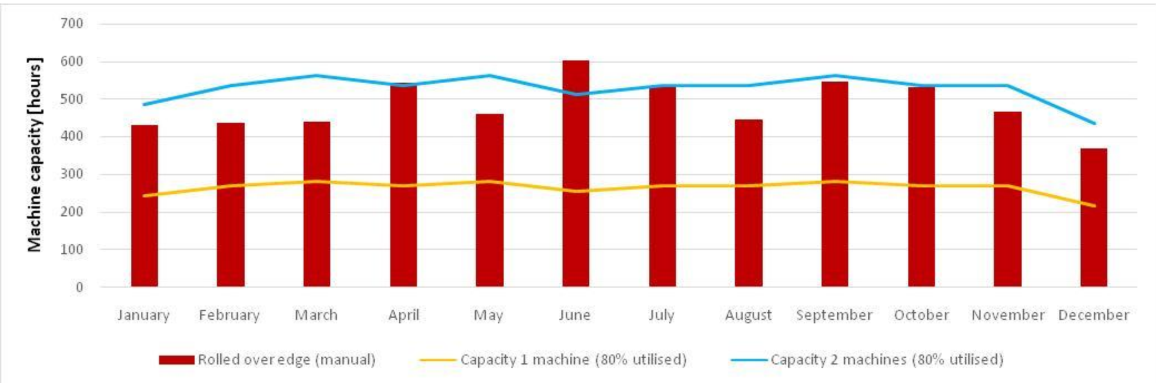

Figure 15 - Overview of accumulated machine capacity for *ROE (manual)* operation for RB and PLB product group types

In this figure, we can see that the operation for these two product group types combined require quite a bit more machine capacity in the month June. This issue could be resolved by shifting around with production. For example, in Figure 12, we saw that production capacity is still available in March. So, the production planner could shift a little bit of forecasted production in June for the RB and PLB product group to March and keep that on stock for three periods. Of course, this requires a little bit of inventory costs, which is not included in the current production plan. Unfortunately, our APP model is not able to also take into account the machine capacities and shift production around in order to also plan machine capacities optimal.

6.2 Sensitivity analysis

Next, we found from Section 6.1.1 that the APP model has chosen to follow, as much as possible, a level strategy. The manufacturing strategy chosen by the APP model is mainly a result of the cost values stated for overtime production and holding inventory. At the moment, we have stated that overtime production is charged 100% higher than regular production, a full regular warehouse costs €5,382.77 per month and the extra storage location costs €9,328.94 per month when fully utilised. If the managers at Air Spiralo® will keep using this APP model, the values of these parameters are bound to change in the future. It is, therefore, important that we analyse how critical the values of these parameters are for the decisions of the APP model.

6.2.1 Holding cost

Let us first analyse the importance of the cost value for a fully utilised regular warehouse. For this sensitivity analysis, we will use our APP model with the scenario for 2016 from Section 6.1. By doing that, we will analyse how sensitive the APP model is to any changes in the near future. Because we do not want to let this sensitivity analysis depend too much on the current situation, we will not use a starting inventory level for each of the product groups. As a result, the APP model is forced to realise all of the forecasted demand through production.

In the figure below, we show how much production is planned through overtime as we multiply the cost parameter of a fully utilised regular warehouse, which we had denoted as s_1, with a different factor. In our APP model, this factor is simply equal to 1.0.

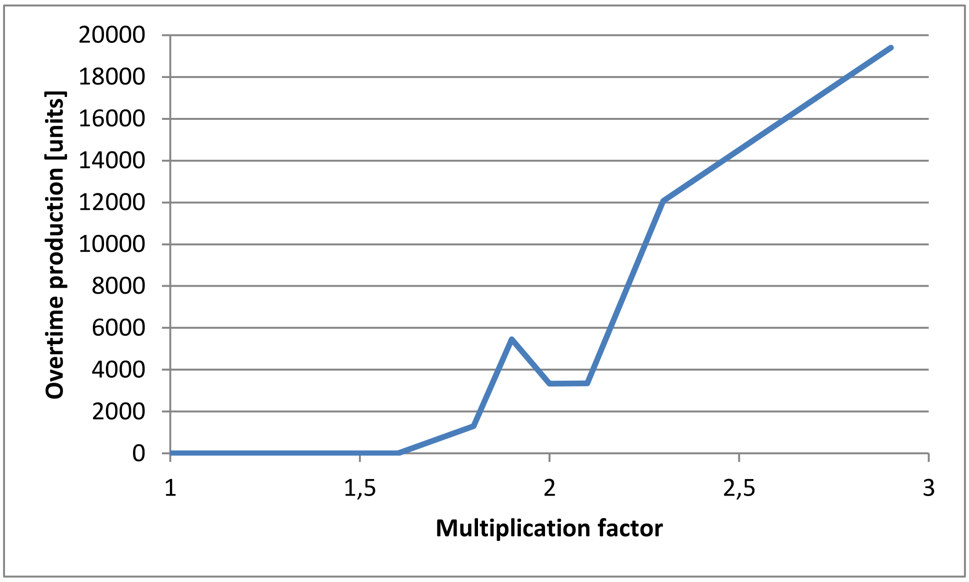

Figure 16 - Use of overtime production as a function of holding cost value for regular warehouse

From this figure, we can see that the APP model starts to plan a lot more overtime production when the holding cost for the regular warehouse is increased with at least 60%. Beyond that point, it becomes cheaper to plan some of the required production simply through overtime instead of having it on stock for multiple periods. Although, between a multiplication factor of 1.9 and 2.2, we see that the APP model again plans less overtime production. What happens is that the model changes the production plan completely. The products that were planned through overtime for a multiplication factor of 1.8, are now planned through regular production time. The cause of this is that we have stated that the objective of the APP model is to find the lowest possible total cost. And so, it happens to be cheaper to change the complete production plan instead of simply planning more overtime production when the inventory cost of the regular warehouse increases. Finally, beyond the multiplication factor of 2.2, the APP model again plans more production through overtime. So, beyond that point, the APP model starts to follow a chase strategy in which it follows demand closely.

So, this result shows us that our APP model is not very sensitive with respect to the holding cost value as we have defined it ourselves. Only when the holding cost turns out to be more than 60% higher, the APP model will change its decisions for the production planning. This means that, if the managers accept our holding cost determination from Section 4.3.4, we can assure the managers at Air Spiralo® that the APP model will not change its manufacturing strategy quickly upon changing the holding cost for a fully utilised regular warehouse.

6.2.2 Overtime production cost rate

Next, we will do a sensitivity analysis regarding the overtime cost rate value. In this case, we keep the holding cost rate for both warehouses unchanged and we will only vary the value of the factor between regular and overtime production cost.

In the figure below, we can see how many products are planned through overtime when we change the multiplication factor for overtime production. In our original APP model, this factor is equal to 2.0.

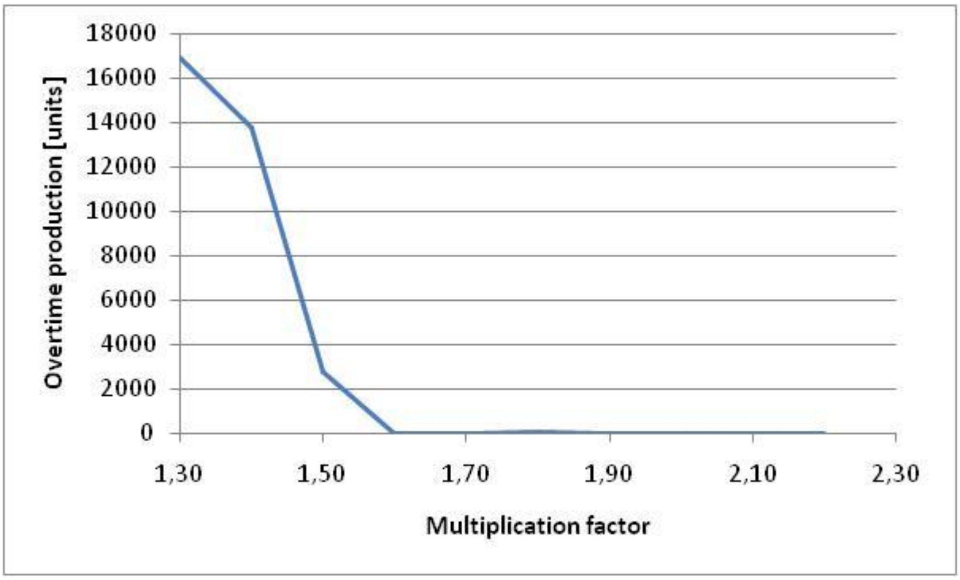

Figure 17 - Use of overtime production as a function of overtime cost rate

From this figure, we can see that the cost rate for overtime production is allowed to decrease at most to a value of 1.6 times the cost rate for regular production. As soon as overtime production costs less than 1.6 times regular production, the APP model starts to plan a lot more products through overtime. So, at that point, the APP model also starts to follow the chase strategy. Again, the APP model does not change its decisions for a cost rate factor higher than 2 times the cost for regular production because it already found it optimal to plan no overtime production for the current cost rate value.

So, this sensitivity analysis shows us that the cost rate value is allowed to vary a little bit. But, as we discussed in Section 4.3.6, we have two possible choices for the overtime production cost rate. It can either be set to1.5 or 2.0 times regular production cost. From these results, we can see that the manufacturing strategy in the APP model changes dramatically when the cost rate value decreases more than 0.4 with respect to the current value of 2. Therefore, the managers should make sure this cost rate value is always representing the situation at Kentel. For example, if overtime production is not done in evening-days or weekend-days anymore, the cost rate value should be changed to 1.5 times regular production cost and the APP model should be re-run to find the optimal production plan.

6.3 Possible cost improvements

Know that we have analysed the optimal production plan for 2016 with the current situation at Kentel, it would also be interesting to see the effects on the output of the APP model when we change some of the parameter values. By changing the value of some parameter values, we can try to search for some possible improvements for Air Spiralo® regarding production planning.

6.3.1 Changing the labour capacity

The most interesting aspect of the model is to change the available FTE for production. For 2016, the target was to use a total amount of 80 FTE each month. As we saw in Figure 13, the APP model had to hold quite a bit of inventory in the months May and April in order to meet forecasted demand in the successive months. Therefore, it could be beneficial to increase the amount of available worker FTE such that less inventory is required. In the figure below, we have shown what happens to the total cost from the APP model when we change the amount of available FTE for production.

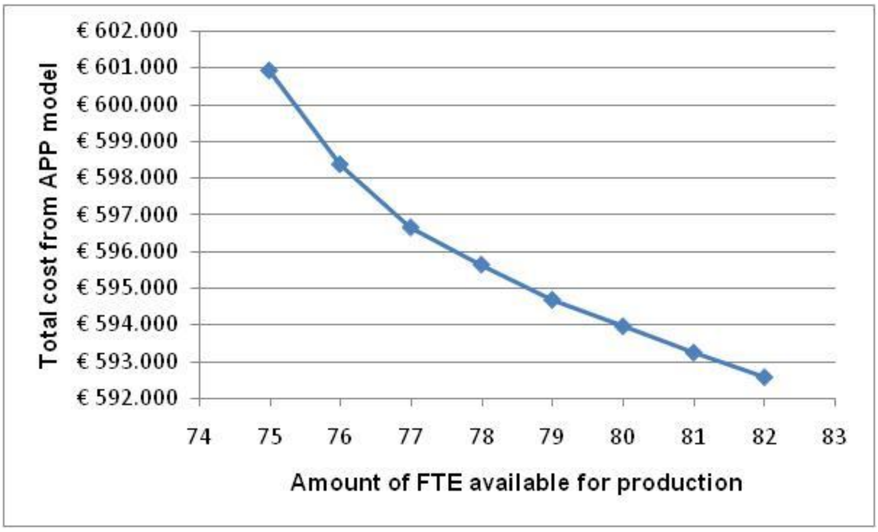

Figure 18 - Effect of changing amount of available FTE

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From this figure, we can see that it is not sensible to increase the amount of available FTE for production. Adding two full time workers to production, and so ending up with a total of 82 of available FTE labour capacity, only decreases total cost with about €1,300. This does not outweigh the costs of paying salary for these workers.

On the other hand, we can see that it is profitable to use fewer workers in production. From Figure 18, we can see that the APP model is able to still find a feasible solution with 75 FTE and the solution is only about €7,000 higher than our original solution from Section 6.1 with the 80 FTE. This, of course, is only a small price to pay compared to the benefit of not having to pay 5 workers if we take into account the fact that one worker has a yearly salary of about €10,000.

What is also interesting to see, is that the APP model still does not require the extra storage location. With 75 of available FTE for production, the APP model has planned a maximum of 118 pallets in the month May. This shows that having less worker FTE will not put a lot of pressure on the available warehouse capacity.

6.3.2 Increasing productivity

Finally, we will analyse what happens to the production plan from the APP model when we increase productivity at Kentel. As we mentioned in Section 4.3.5, the target is set for the workers at Kentel to have a productivity of 85%. The remaining 15% is spent to setting up the machine, training, but also the non-productive hours. The non-productive hours are, for some part, a result of workers having to wait for a shift leader to help him set-up the machine or having to wait for materials to perform the operation on the machine. At the moment, the target is set for 2016 to have about 10% of non-productive hours in each working shift. This means that, if the managers are able to improve some of the causes for the non-productive hours, quite some improvements can be made.

First, as we saw in the previous section, the current budgeted number of 80 FTE of worker capacity is easily sufficient to meet forecasted demand in 2016. From the results, we found that forecasted demand can also be met with 5 FTE less. So, it would not make sense to analyse the effect of increasing productivity while having 80 FTE available for production as it will have little effect on the production plan. So instead, we will analyse the effects of improving productivity for using 75 FTE in production. The change in objective value of the APP model as we change the productivity parameter value can be seen in the table below.

Productivity	Total cost APP model
85%	€600,911
86%	€598,899
87%	€597,264
88%	€596,356
89%	€595,604
90%	€594,880

Table 19 - Analysis of the effect on total cost after improving productivity

From this table, we can see that the output of the APP model decreases with €3,647 when productivity is increased from 85% to 87%. This cost decrease is mainly a result of the fact that the APP model does no longer have to plan production through overtime. So, where the APP model was forced to plan overtime production with 75 worker FTE and productivity of 85%, it can leave out overtime production already when productivity is increased with only

2%. Moreover, if the managers are able to increase productivity with 2%, it also means they need 2% of the 75 FTE, or roughly 2 workers, less for production. Having two workers less needed in production translates into a yearly cost saving of about €20,000. And so, in total, increasing productivity with only 2% actually results in a cost saving of €23,647 every year. So, this shows us that this is quite an interesting topic for the managers at Air Spiralo® to try and improve upon in the future.

6.4 Summary

In this chapter we have used our APP model to plan production for Kentel for the year 2016 and discuss the optimal manufacturing strategy for Air Spiralo®. Also, we have tested how much the cost values for overtime production as well as holding inventory in the regular warehouse are allowed to change before the decisions of the APP model change completely. And finally, we have analysed some possible improvements for Kentel. Based on all of the results, we can conclude the following.

- According to our APP model, inventory should be built up in the months leading up to the summer. In the summer period, not a lot of FTE is available for production and so a big part of forecasted demand should be met from on-hand stock.
- Based on the production plan from our APP model, the optimal manufacturing strategy for Kentel is to follow a level strategy. As a result, no overtime production is necessary. In the months where demand is not very high, extra production should be planned such that inventory is built up.
- The cost value for holding inventory in the regular warehouse is allowed to increase at most 60%. If holding inventory is any more expensive, the APP model will start to plan overtime production as well.
- The cost value for overtime production is allowed to decrease to a multiplication of 1.6 times regular production before the APP model changes its decisions significantly. This means that as long as overtime production is charged 60% higher than regular production, the APP model will not choose to plan overtime production.
- Our APP model estimates that it is profitable to lower the number of FTE in production with 5 to a total of 75. With 75 FTE, yearly costs increases with about €7,000; which is only a small amount compared to the cost savings of having 5 FTE less in production.
- It will also be profitable for the managers at Kentel to improve the productivity of the workers. Our APP model estimates a yearly cost saving of €23,647 when productivity is increased with 2% for a total use of 75 FTE instead of the 80 FTE budgeted for 2016. This cost saving is a result of having to plan less overtime production and the fact that about 2 FTE less is needed.

Chapter 7
Implementation of APP model at Air Spiralo®

Besides analysing the output of the APP model with the demand forecast for 2016, it is also important that we make sure that the managers at Air Spiralo® are able to work with the APP model in the future. And moreover, they also understand the importance of using the APP model, such that they keep using the model after this research project. Therefore, we will describe, in Section 7.1, how the APP model should be used. Then, in Section 7.2, we describe where the APP model can be used to an advantage. And finally, we will explain, in Section 7.3, which parts of the APP model should be made up to date and by whom.

7.1 Using the APP model

First, the APP model should mainly be seen as a tool that helps to analyse some possible scenarios or can be used as a background check when weekly or daily production plans evolve over time. For example, the managers could use the overview of required inventory from the production plan for 2016 as an upper bound on the inventory levels during operational planning. This has to do with the fact that the APP model is a planning model on a tactical level. It cannot be used to replace the operational production planning functions, because the APP model does not have the item details to do so.

Furthermore, because the APP model only considers monthly time buckets, we do not advise the managers at Air Spiralo® to run the APP model as soon something changes in the demand forecast. Changing the demand forecast will automatically change the decisions of the APP model. For example, it could happen that, with the new forecast, it turns out to be better to keep a lower amount of capacity stock throughout the planning horizon. Such a difference in capacity stock can probably not be realised easily in a short period since inventory first has to decrease again. This automatically affects the use of labour capacity and so, fewer workers are needed for a shirt time; this does not match the preference of working with a level production strategy. One other reason is that the APP model does not include, at the moment, a frozen period. So, whenever the APP model is run, the first few periods are also allowed to change. This is actually not very practical, because it could happen that different inventory levels suddenly seem better for the first couple of periods. If the managers would then try to follow these new decisions, it would create a lot of nervousness again in the production plan and the communications between Kennemer Spiralo® and the manufacturing facility Kentel.

Furthermore, as we mentioned in Section 2.2.2, the first three months of the demand forecast can be given with enough certainty. So, the first three months of the forecast will not change a lot. Therefore, we advice the managers at Air Spiralo® to only run the APP model every three months. By doing this, we will create as little nervousness as possible in the production plan. Every three months, the first three periods of the rolling horizon are forecasted with a lot more certainty than three months earlier. So, this allows the decision maker to always use the most accurate forecast for the first three months.

7.2 Advantages of using the APP model

Next, let us now explain where the APP model will prove its usefulness. As mentioned earlier, the APP model should be used to check whether the amount of used overtime production and inventory at Kentel is still below the optimal levels. As we explained earlier, the output of the model cannot be used to manage the daily production planning routines, but it could be used as a background check. So, for example, if a big difference is found between the output of the APP model and reality for a specific month, the managers should reflect on themselves whether the production plan is still followed as originally planned by the APP model and what the reason is for such a big difference.

One other advantage of the APP model is that it requires little knowledge of production planning to understand the output of the APP model. For the actual on-line operational production plan, a lot of knowledge is required regarding the experience of each individual worker as well as the required set-up times of machines. In the APP model, this level of detail is left out to speed up the computations. Furthermore, the decisions regarding production planning are made by the model itself. As a result, the decision maker only has to know how the different parameter values were determined and what the output of the model actually means. For example, the decision maker should be aware of the available machine capacities, since the APP model does not check this when searching for the optimal production plan. To help the decision maker check the available machine capacities, a spreadsheet is created in which a graphical representation is shown of the required machine hours against the available machine hours each month. Here, we have plotted the available machine hours for only 80% of full capacity to account for uncertainty in operational planning. If the required machine hours from the production plan are higher than available machine hours, the decision maker should be able to find a solution for this by discussing it with other managers. An example of such an analysis can be found in Section 6.1.2.

Besides the fact that the APP model can be used to analyse possible scenarios with respect to the production aspect, the APP model could also be used to analyse a budget scenario. At the moment, the managers at Air Spiralo® make a yearly budget plan for Kentel with the help of a demand forecast for that year. This budget plan is used to, for example, check how many employees will be necessary for production or in the warehouse that year. But, as we have seen in Section 5.1, the APP model is quite accurate with respect to estimating the required production cost for labour and machine production. So, instead of calculating the budget plan from the forecast for individual products, the managers can also use the APP model to calculate such a budget plan. The advantage of using the APP model here is that it is able to compute such a budget plan with less time, because it requires less information about the cost price of each individual product.

Finally, the managers at Kentel currently use the three-month demand forecast on product level to calculate, amongst others, the required machine and labour capacities. As soon as the demand forecast changes, the managers at Air Spiralo® have to redo these calculations such that they know exactly the required amount of capacities. With the APP model, the managers only have to check whether this change in the demand forecast has a significant on the accumulated demand forecast for a product group. For example, it could be that customers order different diameters, but still require the same kind of product type. Then, for the APP model, the demand for the respective product group actually stays unchanged. And so, there is no need of redoing the calculations for the required capacities.

7.3 Updating parts of the APP model

As the managers keep using the APP model, many of the parameter values are bound to change. Therefore, it is important that we describe how the APP model should be updated. And more importantly, who should be assigned to any of these tasks.

The most important aspect of the APP model is the process time per operation type for each product group. As we explained in Section 4.3.3, these process times are a result of analysing the BOM information of each of the products that are included in the APP model. As a result, the accuracy of the process times in the APP model can only be as good as the information shown in the BOM structure of each product. At the moment, the production planner at Kentel is mainly responsible for updating the BOM information of the products at Kentel. Because we advice the managers at Air Spiralo® to run the APP model every 3 months, it is best practice to try and update this BOM information every 3 months as well. And, if the BOM structures are actually changed, the decision maker should update the information in the APP model as well. To do this, the decision maker can consult the manual in Appendix D.

Furthermore, it is also important that the information regarding the number of items that fit onto a pallet is up to date in the APP model. As explained in Section 4.3.5, that information is used to compute the average number of items that fit onto a pallet per product group; which, in return, is used to relate the inventory levels to the holding cost function. At the moment, this information is managed by the warehouse supervisor at Kennemer Spiralo® and should, therefore, be updated by him every 3 months if a change is necessary.

Next, it is also important that the most accurate values are stated for the available FTE for production. For those values, the APP model will check whether regular production capacity is still sufficient. As a result, the output of the APP model strongly depends on the accuracy of those values. At the moment, the project manager at Kentel is mostly responsible for determining the required number of workers for production. So, before running the APP model, the decision maker should discuss with this project manager at Kentel whether the available FTE for production in the APP model resembles the actual numbers at Kentel for the next 12 months.

As explained in Section 4.3.2, the APP model uses the cost rates of each machine type to compute the machine costs in the objective function. In this research, these cost rates were extracted from the Excel sheet in which the cost prices have been calculated. In that Excel sheet, the cost rates for machines were calculated by the financial manager at Kennemer Spiralo®. It is, therefore, important that the decision maker discusses the cost rate information with the financial managers before he runs the APP model. The financial manager, on his part, should try to make sure the cost rates for each machine type are up to date to ensure the APP model is able to compute the most accurate machine cost.

One of the other critical parts in the APP model are the cost values for holding inventory in the warehouses. For the given holding cost values, the APP model will decide whether to hold items as inventory or plan overtime production. As we have explained in Section 4.3.4, the holding cost rates are currently calculated from analysing some cost aspects related to the warehouse locations at Kentel. As the APP model is used over a longer period, many of these cost aspects are bound to change. And so, the managers should make sure that these values are still up to date. Many of the cost aspects regarding the holding cost are checked periodically by the financial managers at Kennemer Spiralo®. As soon as the financial managers change some these cost values, they should update this also in the APP model such that the most recent holding cost values are used.

7.4 Summary

To summarise this chapter, we have given an overview of the different parts of the APP model that need to be updated regularly and who should be assigned to those tasks in the table below.

Aspects of the APP model	Production planner (Kentel)	Project manager (Kentel)	Warehouse supervisor (Kennemer Spiralo®)	Financial manager (Kennemer Spiralo®)
BOM information of products	X			
Information "*pallet quantity*" per product			X	
Available FTE for production		X		
Cost rate per machine type				X
Cost values for aspects of warehouses				X

Table 20 - Overview of responsibilities for APP model information

From this table, we can see that some people are given the responsibility for multiple parts of the APP model. The management at Air Spiralo® should make sure these people know their responsibilities and review the information on time before running the APP model.

Chapter 8
Conclusion and recommendations

In this research, we aimed to develop a production planning model that is able to find the optimal production plan on tactical planning level for the manufacturing facility Kentel. In that way, the model can help the managers at Air Spiralo® to analyse the optimal production plan as well as inventory at their manufacturing facility Kentel. In Section 8.1, we will give an overview of our findings regarding the research goals as well as answer the research questions set out for this thesis. Finally, in Section 8.2, we will discuss some possible improvements regarding the APP model as well as give some possible steps for further development.

8.1 Conclusion

Our first goal was to set up an appropriate decision making model on a tactical level that includes as many of the requirements given by the managers at Air Spiralo®. For this research goal, we can conclude the following.

- We have set up an Aggregate Production Planning (APP) model that aims to find the lowest possible cost regarding production and inventory while meeting forecasted demand for a rolling horizon of 12 months.
- The cost of production consists of worker production, both through regular time and overtime, and machine production.
- This APP model uses a piecewise linear holding cost function to model the use of two different warehouse locations at Kentel; for which the holding cost per pallets differs.
- The APP model is capable of computing the required machine hours from the resulting production plan.

Second, the goal was set to let the APP model search for the optimal production plan for the year 2016, discuss the optimal manufacturing strategy and find some possible cost savings by changing the values of a few parameters. Based on the results, we have concluded the following.

- Overtime production has to be avoided at all costs at Air Spiralo®. Based on the cost values found for production and holding inventory, it is cheapest to keep items on stock for multiple periods than to plan overtime production.
- The optimal manufacturing strategy for Kentel is the level strategy; meaning the APP model will plan production in earlier periods and build up capacity stock to meet demand in periods where labour capacity is insufficient.
- It is profitable for Air Spiralo® to use 5 FTE less for production at Kentel. Costs are increased with €7,000; which is far less than having to pay for 5 FTE.
- Improving productivity of the workers from 85% to 87%, after also lowering the number of FTE with 5, results in a yearly cost saving of €23,647. This cost saving is a result of having to plan less overtime production and the fact that about 2 FTE less is needed.

Finally, the output of the APP model has shown that it is best for the manufacturing facility in Poland to hold capacity stock for a few periods. By doing that, they can keep a level production with the lowest number of required FTE over the year.

8.2 Recommendations

Because of time restrictions, we were not able to include all preferred aspects into the APP model. Therefore, we will give a list of possible improvements for the APP model and describe them briefly below.

1. *Discuss the correct cost value for overtime production*

As we found from the sensitivity analysis from Section 6.2.2, the most important part of the APP model is the value set for the cost rates for overtime production. If that value is not set correctly, i.e. reflect the situation at Kentel, the APP model will make the wrong decisions. Based on interviews with the managers at Kentel, the choice was made to set the cost rate for overtime production twice as high as for regular production. As a result, we have stated overtime production during a month is always planned beyond regular shift time. If it happens that overtime production is also sometimes performed during regular shift time, we have to account for this by setting the cost rate a little lower. Based on the sensitivity analysis from Section 6.2, it will be crucial if the cost rate for overtime production is found to be lower than 1.6 times regular production. We, therefore, strongly advice the managers at Air Spiralo® to keep thinking about the most correct cost value for overtime production in a month.

2. *State upper bound on machine capacity per operation type per month*

When the manufacturing flow lines have been set up at Kentel and the managers have gained some more experience with organising them, it could also help to state the machine capacities as upper bounds for the planning model of the APP model. At the moment, we allow the required machine capacities to be planned without any upper bounds. But, as we have shown in Section 6.1.2, it is quite difficult to analyse whether enough machine capacity is available for the operation type. It could be better for the APP model output to state an upper bound on the available machine capacity for every manufacturing flow line and let the APP model search for the optimal production plan. To include this in the APP model, the model should be expanded with a parameter stating the allowed machine hours each month. For this, some of the model aspects from Koltai and Stecke (2008) could be used again.

3. *Implement a holding cost function dependent on the product group type stored*

During the determination of the average value of a full pallet in Chapter 4, we noticed that there is actually quite a difference between the product group types. To calculate the holding cost values for the regular warehouse and the extra storage location in Chapter 4, we simply used the average value of a pallet. It would actually be better to make a distinction between the product group types. So, the product groups for which the value of a full pallet is low, should be preferred to keep in storage by the APP model. By doing that, the risk of keeping a lot of valuable items on stock is minimised. Therefore, we advice the managers to find a way of implementing this distinction between product group types as it will improve the performance of the APP model.

4. *Include a safety stock to account for uncertainty in demand forecast*

For this research, the choice was made to not include a safety stock for each product group type in the APP model. As mentioned often during this research, the demand forecast at Air Spiralo® is only accurate for the first three months. It would, therefore, be useful to include a safety stock for each product type to account for any possible deviations in the future. This will improve the usability of the production plan from the APP model and also lowers the model’s sensitivity for changes in the demand forecast during the 12-month planning horizon. Especially when the managers lower the number of FTE to the recommended number of 75, the output of the APP model will be very sensitive with respect to the accuracy of the demand forecast.

5. *Create an Master Production Schedule based on the output of the APP model*

Furthermore, now that an APP model has been developed for Air Spiralo®, it would be a good idea to also develop a Master Production Schedule (MPS) model. In such an MPS model, the output of the APP model can be disaggregated to item level again and an optimal production plan on a weekly basis can be made. This will allow the managers at Air Spiralo® to have an optimal production schedule while keeping in mind, for example, the batch quantities at Kentel. This latter part, as briefly mentioned in Section 1.2.1, is something that Air Spiralo® is having difficulties with as well.

6. *Increase the number of products used in the model to lower sensitivity with respect to possible change in demand behaviour*

Finally, it would help to try and include more products into each product group. As we have seen in Section 5.1, the APP model is really accurate regarding the computation of required capacities and the resulting production cost. At the moment, the APP model is far within the two percent error target. So, the product group characteristics are allowed to be defined a little bit less accurate such that the APP model is not so sensitive to changes in the demand forecast characteristics as we have seen in Section 5.4. As a result, the managers could use the APP model for a longer period before revising all of the different parameter values.

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Appendix A

A.1 Linear programming problem

Linear programming is a technique that has been widely adopted by many industries (Wagner, 1969). In an LP model decision variables have to be defined which van be altered in the objective function. The values of these decision variables should stay within pre-defined bounds. These bounds are otherwise known as constraints. The coefficients that are set for the decision variables in the constraint are called the technological coefficient. At the end of the model a sign restriction is set for each decision variable. This can either state that a decision variable should be nonnegative or that it should be an integer. The goal of the LP model is to find the most optimal solution regarding the objective function, which can only consist of variables that do not interact with each other. If variables are multiplied with each other in the objective function or constraints the model is not linear anymore. The optimal solution can be found by maximising or minimising the objective function. But a mix of minimising and maximising objectives can be used as well (Winston, 2004).

In case of the basic linear APP models a few underlying assumptions exist. For instance, the product demand is said to be deterministic and the production cost for the given planning period are strictly linear (Nam & Logendran, 1992). These assumptions are immediately the downsides of this technique. In practice the demand is never deterministic. And it is also debatable whether the cost functions within a company are linear.

A.2 Demand behaviour of the product A counterpart

Just as for product A demand from chapter 2, the effects of changing market demand can be clearly seen in the figure below. At the point where customers started ordering product A with KEN-LOK® seal, we can clearly see a decrease in demand for this product.

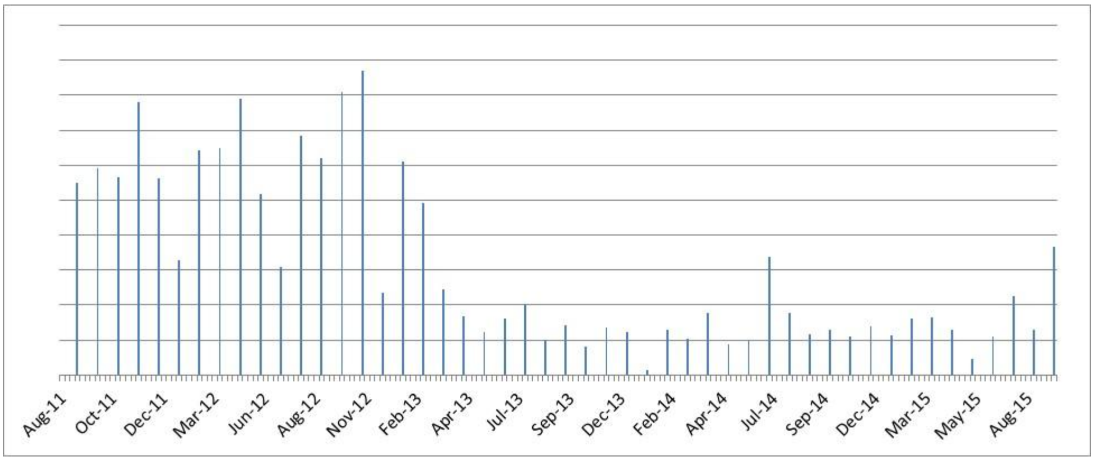

Figure 19 - Demand of product A counterpart (2011-2015)

Appendix B

B.1 Inventory calculations at Air Spiralo®

To use the cycle service level, a safety factor k will have to be derived in order to maintain a certain safety stock. This safety stock is then used to account for uncertainty in lead time demand and thereby not running out of stock during replenishment. To calculate this safety factor, a probability distribution will have to be chosen which should resemble the demand distribution during lead time. For this chosen probability distribution, the safety factor times the standard deviation shows what the probability is that demand can be met from on-hand stock during lead time. Then, in order to find the safety factor necessary to meet a certain service level, one should take the inverted probability distribution and insert the required service level. At Air Spiralo®, the safety factor is calculated for all the products from the standard normal distribution. For that probability distribution, the standard deviation is equal to 1. So, the formula for this calculation look as follows.

$$k = \Phi^{-1}(P\{no\ stockout\ during\ replenishment\}) \tag{42}$$

In this formula, Φ^{-1} represents the inverse of the cumulative standard normal distribution.

After this safety factor has been calculated, the safety stock (SS) level can be determined. The following formula, which we also know from inventory policies using cycle service levels, is used to calculate this parameter value for each end-product.

$$SS = k \cdot \sigma_D \cdot \sqrt{L} \tag{43}$$

The parameter σ_D stands for the standard deviation of demand per unit of time. And L denotes for the manufacturing lead time of the product, which should be in the same unit of time as demand. This manufacturing lead time is known and assumed to be deterministic. In case of Air Spiralo®, this is mostly true. Only when problems occur, such as breakdowns or lack of raw materials, this lead time may deviate.

After the safety stock has been determined, the re-order level s can be calculated. This re-order level is calculated such that the safety stock level is expected to be reached when the production order arrives at the warehouse. A factor, let us call it c, is used by the stock manager to account for significant market changes. It is derived by comparing the old sales forecast, which was calculated at the start of the year, with an extrapolated yearly sales forecast. This extrapolated sales forecast is derived by summing up the realised sales of the previous month and the forecasted sales of the three upcoming months and then extrapolating it to 12 months by multiplying it with three. The factor c is then equal to the extrapolated sales forecast divided by the old sales forecast. In most cases, this factor c is set equal to one. Only if the factor c deviates significantly from one, it is applied to the inventory calculations. This factor c mainly allows the inventory manager to somewhat anticipate on market changes. In the end, the formula for calculating the re-order level s can be written as following,

$$s = c(SS + E(D) \cdot L) \tag{44}$$

The parameter $E(D)$ stands for the expected weekly sales. The part $E(D) \cdot L$ is also known as the mean lead time demand. This formula is, apart from the factor c, consistent with the formula we know from theory. The re-order level should be placed such that the safety stock is expected to be reached when the production order arrives, i.e. after this mean lead time demand.

After these two inventory parameters have been calculated, the order-up-to-level S can be derived. First, the purchase quantity is derived from the expected yearly sales for the end-item and a pre-defined replenishment frequency. For each type of product class a replenishment frequency is stated. This replenishment frequency is mostly based on the warehouse capacity and given lot sizes of the supplier. To which type of product class an end-product belongs is determined via the ABC-classification. At the moment, the company bases this ABC-classification on the sales quantity and cost price of the end-product. The products that resemble 80% of the total value of multiplying sales quantities and cost prices are stated as class A products. The next 15% is stated as class B products and the remaining 5% as class C. Class A and B are bought, preferably, on full pallets; the class C in full boxes. In the end, the following formula is used by the inventory manager for calculating the order-up-to-level S,

$$S = s + Roundup\left(\frac{\frac{E(D_{year})}{Replenis\ hment\ \ frequeny}}{Q_{palle\ torbox}}\right) \cdot Q_{palletorbox} \tag{45}$$

In this equation, we can see that the company does not account for any undershoot. These equations are based on lot-for-lot demand, which is actually not often the case in practical situations. Only when the inventory level is actually equal to the re-order level, the above equation is appropriate. Whenever the inventory level has dropped below the re-order level, the amount of undershoot, being equal to the re-order level minus the inventory level, should also be ordered in order to reach the order-up-to-level S again.

The value of $E(D_{year})$, the expected yearly demand, from this formula is calculated for each end-product by looking at two effects. First, the realised sales of the previous 12 months are summed up. This will give an estimate of expected end-product demand for the full year. Next to that, so-called 'changes' are incorporated as well. These 'changes', which are stated per customer, are calculated based on major deviations from the normal demand pattern. These deviations are usually a result of customers from England and Belgium. Customers from Belgium are relatively new to the company, so no reliable historical sales are available. The customers from England are usually involved in project-work; therefore, they are very difficult to predict. Furthermore, changes could also be applied when significant increase in demand is expected for certain customers. In the end, these two calculations are combined to give an estimate for the expected year sales of end-products. After that, this yearly demand is divided up into economical batch sizes based on the replenishment cycle. Then, this economical batch size is converted into a more practical batch size by re-sizing it with the quantity that fit onto a pallet or into a box. This more practical quantity is then used to calculate the order-up-to-level S. Normally, one calculates an optimal batch quantity from the EOQ formula and adds this to the re-order level to come up with the order-up-to-level S. But, at the moment, the company has not been able to define an accurate order cost per end-item, which is important for the EOQ formula (Axsäter, 2007). Therefore, they have chosen for this formulation instead.

The formula for the order-up-to-level S looks a lot like a (s, nQ)-inventory policy. But, with that policy, the order quantity is determined such that the inventory level rises above the re-order level again in case of undershoot (Chen & Zheng, 1994). That differs a little bit from the policy at Air Spiralo®, because here the inventory levels, also when undershoot occurs, have to be raised to the order-up-to-level S.

Appendix C

C.1 Output from APP model in Data validation

Summary of total costs		January	February	March	April	May	June	July	August	September	October	November	December	TOTAL
Regular production	Labour	€30,475.35	€27,490.01	€28,637.57	€30,820.27	€40,445.41	€37,182.21	€39,119.67	€31,756.05	€35,527.07	€41,118.74	€31,420.18	€20,453.38	€394,445.91
Overtime production	Labour	€ -	€-	€ -	€ -	€-	€-	€-	€ -	€ -	€ -	€ -	€ -	€ -
Machinery costs		€16.927.41	€15,269.44	€15,834.92	€17,081.34	€22,451.35	€20,639.63	€21,630.27	€17,558.61	€19,876.89	€23,005.30	€17,630.75	€11,665.20	€219,571.12
Inventory holding costs		€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
TOTAL		€47.402.76	€42,759.45	€44,472.50	€47,901.61	€62,896.76	€57,821.84	€60,749.94	€49,314.66	€55,403.96	€64,124.04	€49,050.92	€32,118.58	€614,017.01

Table 21 - Overview costs from APP model for historical data validation

Appendix D

D.1 User manual for APP model

D.1.1 Introduction

In this user manual, the different parts of the APP model, as developed by Alexander Krediet during his master thesis at Air Spiralo®, will be explained. In essence, the APP model is used to search for the optimal production plan based on a given demand forecast for the next 12 months. To be able to plan production over such a long period, the model only considers production for the whole month. The detail of daily production planning is not included. Therefore, the APP model should not be used as a replacement of the daily planning tools.

The APP model will make use of regular production, overtime production and temporary inventory to be able to meet this forecasted demand in each respective month. For the research of Alexander Krediet, the choice was made to only include the top 80% of production volume at Kentel, which will be, potentially, produced across manufacturing flow lines.

In the end, the goal of the APP model is to meet this forecasted demand with the lowest possible cost related to production at Kentel. This means that, if regular production capacity is insufficient, it will decide whether it is best to plan overtime production or increase production in earlier months and keep those items on stock for a couple of months. Overtime production is more expensive than regular production because workers have to be paid extra to work in overtime. Holding inventory will also cost extra, because pallets have to be stored; which requires the use of available storage space as well as handling cost from a worker. The production costs are a result of the average process times for an item from a product group and the respective cost rate for labour production. The machinery costs follow from the required machine hours each month and the respective cost rate for the operation type.

In this manual, the following aspects will be discussed:

<u>Section 1:</u> Setting up and running the APP model

<u>Section 2:</u> Updating product group mixes

<u>Section 3:</u> Updating the operation types

<u>Section 4:</u> Setting up the demand forecast for APP model

D.1.2 Setting up and running the APP model

First, let us explain how the APP model should be used. The APP model is a linear programming problem that is solved using a pre-coded program. This program will enable the user to define the different limitations and goals of the APP model. Because of the required dimensions in the APP model, the choice was made to use a program that is capable of solving large linear programming problems in Excel. This program, called OpenSolver, should be first started up before the APP model is opened. Only then, the program can be used to let the APP model search for the optimal production plan. The program itself can be found in the tab “Data” in Microsoft Excel. All of the required constraints and objective function statements are already loaded into the program, so the user only has to run the APP model, i.e. press “Solve model”, when he or she is sure all of the parameters are set correctly. Important parameters are, for example, the cost rate for overtime production or the costs related to storing items as inventory. In the following sections, a description of how to set up all of the parameters in APP model can be found.

Input parameters

One of the imporant inputs is the available worker capacity. With this information, the APP model knows exactly how much can be planned via regular production time as well as overtime production. Therefore, the first few rows are used to state the productivity of a worker as well as the amount of breaks one worker has on a workday. With those values given, the amount of available production hours can be calculated from any given amount of available FTE. Also, the amount of available overtime per regular production hour is stated. For example, the user could state that a worker is allowed to work half an hour extra for every hour he or she works.

After that, the holding cost for a pallet per month at Kentel is given; both for the regular storage space as well as for the extra storage space. These values have been determined in Section 4.3.4 of the master thesis of Alexander Krediet. In essence, these values are a result of determining the different cost aspects for holding pallets in the storage racks at Kentel. The values for the different cost aspects can be found in a seperate tab in the APP model.

Below the holding cost parameters, the machine cost rates for the different operation types can be found. For the product groups currently included in the APP model, 25 operation types were found in the BOM structures. The cost rates have been defined in the cost price calculations from the Cost Price Steering Group and are simply pasted into the Excel sheet. Below these cost rates, the labour rate for regular and overtime production can be found.

After that, an overview of the different capacity limitations is given. First, the warehouse capacity at Kentel is defined. This is both for the regular warehouse capacity (Hall 1) as well as for the extra warehouse capacity (Hall 3). In the regular warehouse space, only a part of the available storage racks can be used to store finished items, because some storage racks used for work in progress and KANBAN items. Therefore, the number of available pallets for storage is not equal to the maximum available pallet places at Kentel. The same goes for the storage in Hall 3.

Then, the calculations for the available worker capacity in each month are shown. These calculations are done in the same way as in the productivity report for Kentel. Here, the number of FTE that is currently employed or is expected to be employed in each month is shown first. From these values, the number of FTE that is expected to be on holiday, will be reported as sick and will be working as service workers is subtracted. Next, we also account for the fact that ony 80% of production volume is included in the APP model.For these production quantities, only 70% of available FTE is required. So, the available FTE for production is multiplied with 0.70. This results in the amount of FTE that is available for production in the respective month. Then, these values should be converted into units of hours such that the planned production quantities can be compared to the available production hours. To do this, the amount of hours one FTE will work in a month is stated. For this, the number of working days and the number of hours per working day are stated. The total amount of available production hours is then computed by multiplying the available FTE for production with the amount of working days and the number of hours per working day. And furthermore, the resulting amount of available production hours is multiplied with the earlier stated productivity in row 3. And finally, below the resulting available production hours in each month, the allowed overtime hours in that particular month is stated. This is calculated by multiplying the number of working days with the working hours per day and the amount of overtime hours allowed per regular working hour.

Then, an overview of the parameters related to the different product groups are given. First, the current inventory level of each product group at Kentel is given. These values are a result of extracting the shelf stock levels at Kentel of each product from the ERP system and then computing a weighted average, using the yearly sales quantities as weight values, for each product group with the products included in the APP model. Next to that, the average required number of pallets per item is given. These values have been calculated from the information for the number of items that fit onto a pallet per product. Then, an overview of the weighted average process times of a product group for a particular operation type, both by a machine as well as by a worker, is given. Here, only the BOM structure of the products included in the respective product group is used. If the operation type is not found in the BOM structure of a product, a process time of zero is stated. The summation of the different process times is given as well; this value represents the total amount of time required to manufacture one item of the respective product group. These values will be used to compute the required production hours, which will be compared to the available production hours calculated earlier.

Below all of these input parameters, an overview of forecasted demand for the different product groups for the upcoming 12 months is given. This forecasted demand is extracted from a different spreadsheet, in which the forecasted demand per end-product is given. A description of how the demand forecast for each product group is defined, can be found in Section 4 of this manual.

Output parameters

Below all of these input parameters and demand forecast, the output of the APP model can be found. This output is created by letting the OpenSolver find the optimal objective function value, i.e. the lowest possible cost required to meet the forecasted demand. First, the number of items planned for production in the respective month will be given; this can either be done in regular production time or in overtime. Below that, an overview of the inventory level for each product per month can be found. This inventory level is simply calculated from comparing the difference of planned production and forecasted demand for the respective product group. These inventory levels reflect the capacity inventory, such that less production is necessary in high demand periods. These inventory levels will be shown graphically in another worksheet in the Excel file, such that the inventory behaviour over the planning horizon becomes a bit more clear.

From this created production plan, the final output of the APP model states the required machine capacities for each operation type. These values can be found at the bottom of the APP model. For each operation type, the required amount of machine hours will be displayed. These numbers are calculated from the amount of planned production quantities for each product group, both in regular and overtime production, and the respective process time for machinery. Below this output, the required amount of pallets for storage each month is shown. These values will be used to compute the related holding cost each month. For example, if only half of the total available pallet places of the regular warehouse is used, the APP model will take into account half the cost for a full warehouse. But, if the APP model wants to store more pallets than available in the regular warehouse location, this is allowed via the extra storage location. For that extra location, a different cost rate is applied for storing the pallets because the housing and handling cost are different for that location.

Cost overview

With the optimal production plan, the model will give the different cost aspects. First, the necessary regular production cost are stated. For this, the amount of regular production hours are multiplied with the cost rate for labour at Kentel. Then, the overtime production cost are shown. The calculations are the same as for regular time production. Only now, the items that have been planned via overtime production and the cost rate of a worker for overtime production are used. From the planned production quantities, the APP model can also compute the machinery cost. This value is calculated by multiplying the necessary production hours of each machine type with its respective cost rate and finally summing up all these costs. And finally, the inventory holding cost are also calculated. For this, the amount of used pallets are multiplied with cost rate of a pallet per month. The summation of all these different cost aspects over the planning horizon can be found in the bottom right corner of the total cost overview. This value will be the optimal value for the objective function.

Graphical overviews

Then, when the APP model has found the optimal production plan, based on the giving rolling forecast, some graphical overviews of the decision variables, such as the planned production quantities or required machine hours, can be found in the other spreadsheets. These graphical overviews will help the user to understand some of the choices of the APP model. For example, the APP model can sometimes choose to plan all of the available regular production hours in a month such that inventory levels of some highly demand product groups are filled. Or otherwise, it could need overtime production in order to meet forecasted demand, because it was not able to build up enough inventories or it turned out to be more expensive. For those months, the graphical overviews will show that production has been planned above the regular labour capacity.

Next to this, an overview is also given of the required machine hours per product group each month. With that information, the user can try to analyse how the manufacturing flow lines at Kentel could be designed. For example, it could be that two or three product groups require almost exactly the available capacity of one machine for a certain operation type. Then, for those product groups, it could be beneficial to arrange the manufacturing lines such that they share one machine of such an operation type. Here, the user should keep in mind that a machine should not be planned to its full capacity, because that will create a lot of waiting time, increase the WIP and manufacturing lead time. A good rule of thumb is to plan a machine to only 80% of its full capacity.

D.1.3 Updating product groups

At the moment, the products from the product groups do not change automatically based on historical sales information. If a significant change has occurred in the historical sales, the products in the product groups should be analysed again. For this, a few steps are necessary. These steps are explained in the following sections.

Making the 80% production quantities analysis for Kentel

The first step is to determine which kind of products cover the top 80% of production quantities at Kentel. For this, the products should be sorted on their production quantities in the last 12 months. From the top 80%, the user should make a pivot table with Excel such that the products are sorted based on product groups. Make sure you count the number of different products within a product group. If it occurs that a product group only consists of one or two products, it is not practical to use it in the APP model. For those products, it will not be beneficial to create manufacturing flow lines at Kentel. Therefore, delete those products from the top 80% analysis and make sure you redo the analysis. In this pivot table, make sure you also analyse the statistics of process time, which is extracted from the BOM information. For these process times value, sum up the structure times for *DirectLabour*. With this process time, compute the average and standard deviation within each group. If the coefficient of variation (CV), which is the standard deviation divided by the average, is larger than 0.40, you should split up the product group such that the CV drops below 0.40 for the smaller groups. For example, the SV product group is split up into products with diameter smaller than or equal to 250 millimetres and products with a diameter larger than 250 millimetres. If it is not really possible to create smaller groups with a CV lower than 0.40 because you will create a product group of one or two products again, delete the products from the top 80% analysis that are a cause for the high CV value. This last part is allowed, because the goal of the APP model is to plan production for the manufacturing flow lines at Kentel. Therefore, the products that have a significantly different process time within a product group are not interesting. Again, after you have removed products from the list, redo the analysis in which you determine the top 80% of production quantities.

After you have found appropriate product groups, sort the products on the respective product group abbreviation alphabetically.

Computing process time per operation type

After you have found product groups in the top 80% analysis for which the CV value is below 0.40, it is important that the average process time for each of the operation types is determined. For this, you should use the macro from the Excel file "*Analysis BOM info with product selection*". In that Excel file, you can simply load the product list with the interesting products from the 80% analysis. The macro will then look up the BOM of each of those products from the ERP system. After the BOM information has been updated, run the next macro with which you can determine the weighted average process time per operation for each product group. In this macro, the sales quantities for a full year are used as weight values. It is important that these sales quantities will reflect the sales quantities in the demand forecast as much as possible. So, it could be useful to try and use the most recent yearly sales values for each individual product. Otherwise, simply use the sales quantities from the last 12 months.

Updating info in APP model

Now that items have been removed or added to the existing product groups or that new product groups are necessary, the respective information in the APP model should be updated. First, it is important that the required pallet space per item of the product group is defined. This information is calculated separately in the APP model in the sheet "*RequiredInvSpacePG"*. Here, you should upload the complete product list from the 80% analysis and look up the quantities per pallet from the ERP system for each product. Based on the defined product groups, the average number of items per pallet for each product group will be determined. Also here, the yearly sales quantities per individual product are used as weight values to calculate the average per product group. Finally, make sure that correct values are taken from the product list, i.e. the correct product group abbreviation is checked correctly between the spreadsheets in the APP model Excel file.

Also update the average process time per operation for each product group in the APP model. For this, you can simply paste the values which were computed in the Excel sheet "*Analysis BOM info with product selection*". Furthermore, make sure that you also update the demand forecast with the correct products. This can simply be done by updating sheet 3 in the APP model. Simply paste the product list from the top 80% analysis. The excel sheet will search for the forecast by using the 'vlookup' formula. Finally, make sure the forecast in the APP model sheet searches for the correct values. This can be checked whether the abbreviations on each of the forecast sheets in the APP model is stated correctly and the same.

D.1.4 Updating machine operation types

As the product groups change in the future, it could happen that different machine operation types need to be used in the APP model. At the moment, the APP model is set up such that the minimum required number of operation types has to be implemented. If a product group is added the APP model that uses a different operation type, this operation type should be added and the redundant operation type has to be removed.

First, the weighted average process time for each operation per product group has to be determined again. For this, the macros in the Excel file "*Analysis BOM info with product selection*" have to be run again. The macro will check all of the operation types and calculates the weighted average (based on the sales quantities stated in the final column of sheet 2) for each of the operation types. After you have let the macro run, delete the operation types for which no process time is used by any of the product groups. After deleting these operation types, simply paste the results in the APP model to update the model with the new process times and machine operations.

Besides that, the cost rates for the machine operations have to be changed as well. Just as for the process times per operation type, only the cost rates for the necessary machine operations have been stated to keep the APP model clear. The information for the machine cost rates can be extracted from the Excel sheet in which the cost prices are determined.

Finally, also update the summary of required capacities. Here, the renewed machine operations have to be stated such that the APP model can calculate the necessary machine hours per operation type.

D.1.5 Setting up the demand forecast

Before the APP model is run, the demand forecast should be made up to date. First of all, the most recent rolling forecast for Kentel, which is generated by the inventory manager, should be implemented in the APP model. For this, a separate Excel spreadsheet is used in the APP model. Here, it is important that the rolling forecast of each month is given next to each other. Furthermore, make sure each individual product is actually forecasted. Some products from the top 80% of production volume are sometimes not denoted as class A products and are, at the moment, not forecasted by the inventory manager.

Then, one should paste the list of all products, which were found to be necessary from the analysis of the top 80% of production quantities, into a different spreadsheet. In this spreadsheet, make sure the correct product group abbreviation is denoted next to each individual product. Then, with the help of the 'vlookup' formula from Excel, the forecasted quantities for each individual product per month are extracted from the rolling forecast in the other spreadsheet. With this demand forecast, the APP model will accumulate the forecast of each month by checking whether the product corresponds to the product group.

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