Optimizing the material flow at Bosch

Supplying the Deventer plant with materials for making heating boilers

Graduation Thesis

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Preface

With this thesis I finish my master Applied Mathematics at the University of Twente. The last 9 months I have worked at Bosch in Deventer with much pleasure. At the beginning of this assignment, the goal was vague: Improve and simplify the current situation with some kind of mathematical model. During the 9 month period, more restrictions became apparent. Wishes and other improvements were constantly suggested, which resulted in a model that changed continuously.

Next to making a model to describe the situation at Bosch, I have learned to program it in Virtual Basic for Applications, which was new for me. Thanks to this new learned skill, the model could be tested with historical data. I am very proud of the final version of this model and of the results that it produced. It was a big bonus for me that my model was implemented at Bosch. This meant that I not only had to pitch my ideas to the highest bosses at the Deventer plant to convince them of the success of this model, but also that I had the chance to implement my own ideas. This was a great experience for me.

During my study, I always had affection with the world of logistics. This resulted in a minor Production and Logistic Management and many courses in my master about Industrial Engineering and Management. This graduation assignment was a perfect mix between logistics and mathematics. It was a real world example of applying mathematics. All the time people ask me what I want to do when I am done studying. Thanks to among others this assignment, I found out that I want to go in the logistic world.

I want to give many thanks to my coworkers at Bosch, which treated me as a worthy colleague. A special thanks goes out to my supervisors at Bosch: Maarten Brouwer, Koos van der Rijst and Marc Weulink. Next to that, I want to thank Johann Hurink for supervising my graduation, especially with reviewing my thesis. I know that I gave him a hard time sometimes, but he stood always by my side. I also want to thank Jan-Kees van Ommeren for reading my final thesis. A last thanks goes out to everybody who supported me during my graduation and in the making of this thesis.

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1. Introduction

This thesis describes the case of supplying the production process of one of the leading manufacturers of heating boilers in the Netherlands. The materials for the heating boilers are provided by multiple suppliers. These wholesalers supply the manufacturer by truck, which causes a large number of trucks delivering materials to the factory. These trucks cannot arrive at the same time, due to the limited capacity at the factory to unload the trucks. This means that the arrival times of all the trucks have to be adjusted to each other. At the same time, it has to be guaranteed that the production does not get to a standstill, due to the fact that the materials for production are not present at the time they are needed. To prevent this, coordination is needed between the arrival times of the trucks and the composition of the corresponding orders. In this thesis a model is developed which coordinates the determination of the arrival times of the trucks and the composition of the orders.

In the following more details on the manufacturer are given and the concrete setting of the relevant case is explained in more detail. Next to a description of the current situation at the manufacturer, both sub problems, the composition of the orders as well as the determination of the arrival times of the trucks, are elaborated. The subsection ends with a more detailed problem statement for this thesis. After that, background information is given about the way how the orders are composed within the considered factory. The system used for the composition of the orders creates a link between the materials that are used in the production of the heating boilers and the materials that are ordered. This is done in a way that the production does not come to a standstill. The section ends with an overview on how the remainder of the thesis is built up.

1.1. The manufacturer

The manufacturer of heating boilers on which this case is based is Bosch. This manufacturer has many divisions, each of which produces different products from laundry machines and screen wipers to heating boilers. The division Bosch Thermotechnology (TT) is responsible for the latter. This division has the mission to design and produce energy efficient solutions for heating, cooling and hot water. To achieve this mission, Bosch TT produces heating systems, heat pumps, commercial boilers, air conditioning and ventilation systems, solar thermal systems, domestic hot water heaters and more. Hereby, Bosch TT produces under different brands; Bosch, Buderus, Junkers, Vulcano, Worchester, e.l.m. LeBlanc, Dalkon, IVT and Nefit.

Bosch TT has over 20 production sites over the whole world, from which 16 are in Europe. At the Bosch production plant in Deventer heating boilers are assembled. The materials needed for this assembly are coming from The Netherlands, Germany, Turkey, some other European countries and Asia.

The predecessor of Bosch TT in Deventer, Nefit, was the first to launch a central heating boiler with high efficiency, the Nefit Turbo. In 1992, Nefit and Fasto B.V. went on together to get a better focus on the market and in 1997 half of the shares were sold to Buderus Heiztechnik GmbH. This made the export rise with 50%. In 2004 Buderus was taken over by the Robert Bosch Group. From this moment Nefit was part of Bosch Thermotechnik. In 2013, Nefit, Bosch and Buderus were brought together to go on as Bosch Thermotechniek B.V.
In the next subsection the considered case for the Bosch TT division in Deventer is explained in more detail and the problem description is given.

1.2. Problem description

In this subsection the case of supplying the Bosch TT division in Deventer with materials is described in more detail. First an introduction is given of the current processes at the Deventer plant. Then, the problem of supplying the factory is described in more detail. This leads to the problem statement.

At the Bosch TT plant in Deventer the production of heating boilers is done following a "just in time" management. Just in time management is a type of production where commodities are only produced when there is a demand for that type of commodity. This means that the materials are ordered dependent on which commodities are produced. A consequence of the just in time management is that the inventory level of materials as well as finished goods is low. This reduces space and holding costs. A disadvantage of just in time management is that a small disruption in the delivery of the materials could cause a standstill in production. To prevent this, a good coordination between Bosch, the suppliers and the transport company HSL is required. The latter delivers the materials from the different suppliers to the Deventer plant.

Currently, the material flow is arranged such that the materials of the suppliers are stored at a local depot of HSL. This transport company delivers the material regularly to the Deventer plant. To optimize this material flow a system called Milkrun is going to be used. The Milkrun system consists of an order part and a delivery part. An order consisting of materials that were just used for the production of heating boilers is send to the supplier. This is done following the just in time philosophy. The supplier needs time to process the order and pick the materials such that a truck from HSL can transport those materials directly to the Deventer plant. When those materials are delivered and unloaded from the truck, the materials are used for the productions of new heating boilers and the cycle starts over again.

The choice for the Milkrun system makes determining the arrival times of the trucks of HSL a complex task. The reason for this is that in the whole supply chain the inventory level is low, which means it is more critical that the trucks deliver the materials on time in order to prevent a standstill in production. A restriction that makes this even more complicated is the fact that at the Deventer plant, there is only one dock to load and unload materials. This means that only one truck can arrive at a time. Next to that, unloading the trucks takes some time such that the unloading of the next truck can start only after that the unloading of the previous truck has been completely finished. One of the goals of the model developed in this thesis is to automatically determine when the trucks must deliver their materials to the Deventer plant.

Next to the most crucial restriction of having only one dock, there are some other restrictions which are described in the next section. In the following, some more details about the problem of supplying the Deventer plant are given which are needed to formulate the problem statement. The description follows the two parts of the Milkrun.

First, the structure of the orders is explained. An order consists of materials that were just used in the production of heating boilers. Due to the just in time management, this relates directly to the demand of heating boilers. The demand consists of long-term customer orders and short-term customer orders. The long-term customer orders create the season pattern, but do not change often. The short-term customer orders come in a week in advance and causes that the demand for heating boilers changes every week. As a consequence, the amount of materials needed for the heating boilers also changes every week. Due to this and the just in time management, the orders differ every time.

An order consists of a list with all the materials that have to be delivered and the amount that is needed per material. These amounts have to be such that the total order can be delivered by one truck. This means that all the amounts of material together must not exceed the capacity of the truck. This can be regulated by choosing the moments that the order is send to the supplier. For this is assumed that all the materials that are on the current order are those that are used in production from the moment that the previous order is send until the moment the current order is send. By regulating these moments, the composition of the orders can be established. Concrete, a Kanban system is used to implement this strategy. In section 1.3 more details are given about this system.

Before going into more detail about the problems with the delivery, a small note has to be made. There is a difference between two types of materials: Small volume materials and great volume materials. The great volume materials are produced by suppliers nearby and are transported by HSL directly from the suppliers to the Deventer plant. The other (small volume) materials are gathered, stored and delivered to the Deventer plant by another transporting company called Veenstra. The trucks that deliver small volume materials are not regarded in this model, but their schedule is considered as input for this model. The reason for this is that the schedule for these trucks is more or less the same every week and that in the nearby future the whole operation regarding small volume materials is going to change, such that scheduling those trucks would become useless.

The most crucial problem with the delivery is that there is only one dock to unload the trucks as discussed at the beginning of this section. Next to that, the impact of the changing demand on the trucks of HSL is great. Those trucks usually deliver six to seven times a day to the Deventer plant, but that can increase to ten times a day. Furthermore, trucks from Veenstra deliver five times a day. Those trucks deliver the small volume materials at fixed times to the Deventer plant. This is not the case for the trucks of HSL. Moreover, other suppliers deliver materials in between the arrivals of the trucks of HSL and Veenstra. Although these suppliers do not use the dock used by HSL and Veenstra, unloading these trucks takes up precious time and man hours. As a consequence, scheduling the arrival times of the trucks of HSL is difficult.

At the beginning of this section the coordination between the composition of the orders and the arrival times of the trucks was discussed. In the current situation, this is reached by linking the two in the following way. The time between the moment when the order is send and the time when the truck arrives is fixed per supplier. This means that if the moments when the orders are being sent are determined, the arrival times of the trucks are fixed. This complicates the problem, because the truck arrival times and moments that the order is send are related.

The goal of this research is to find a good coordination between two aspects, which leads to a feasible supply and which reduces costs as much as possible. In order to reduce the transport costs, Bosch wants to minimize the number of trucks. To achieve this, the goal is to utilize the trucks optimally. As a consequence, the trucks must have a high occupancy. Next to that, the transport costs can be reduced by minimizing the waiting time of the trucks at the Deventer plant. This is achieved by scheduling the arrival times of the trucks in a good way.
Finally, to reduce the production costs, the factory must not come to a standstill. Otherwise losses are made by not reaching the demand of heating boilers. This leads to the problem statement:

How must the Deventer plant be supplied with great volume materials such that the total costs are minimized?

This problem can be divided into different parts:

When must the great volume materials be ordered?

When must the trucks arrive?

Which amount of great volume materials must be ordered?

These questions regard the optimization of the number of trucks. A requirement in this is that the production does not come to a standstill. The problem that is tackled in this thesis is referred to as the Bosch supply problem or the simply supply problem.

1.3. Background

In this subsection a detailed description is given about how the orders are filled. For this, Bosch uses a system called Kanban. The Kanban system is a production control method that links the usage of materials in production and the amount of materials that is ordered. Knowledge about this system is needed to answer one of the questions of the problem statement. In the following, an introduction is given why Bosch chooses this system to fill the orders. Then, the original Kanban system is explained and the application at the Deventer plant is described.

The demand for heating boilers changes every week. Because of this, the amount of materials needed for the assembly of heating boilers changes strongly. To ensure that the production does not come to a standstill, a couple of options are available. One option is having a high inventory level to compensate the strong change in demand. Another option is having a short lead time such that the materials are replenished rapidly. Bosch chooses for the option of a short lead time, because the space at the Deventer plant is limited and because having a high inventory level leads to high holding costs.

To achieve a short lead time, Bosch uses a Kanban system. The Kanban system is described by Y. Sugimori et al. in [SKCU77]. The Kanban system was developed by the vice president of the Toyota motor company, Mr. Taiichi Ohno, around 1953. It makes sure that the materials that are being used in production are being ordered one to one. For this, in the Kanban system a sort of order card is used. This is called the Kanban card.

In the Toyota factory there was a production area, where parts were produced and an assembly area, where all the parts were assembled. The supply from the production area to the assembly area was done by containers holding the parts produced at the production area. Each container got a Kanban card attached to it before sending the container to the assembly area. Whenever the workers at the assembly area were finished assembling all the parts from the container, the Kanban card was sent back to the production area. This would indicate that all the parts from the container were used for assembling the Toyota cars and new parts were needed in order to continue assembling cars. The workers at the production area then sent a new container holding the same parts to the assembly area and attached the same Kanban card on it again.

The Kanban system at Bosch is slightly different, but is based on the Kanban system developed 60 years ago. The Kanban system at the Deventer plant is used between the production area and the department of internal logistics. At this department, all the materials from the different suppliers are delivered, before they are distributed among the production area. From the department of internal logistics, the order is also sent to the supplier. During the unloading of a truck, all pallets get a Kanban card attached to it. The Kanban cards consist of two parts. One of those is the information part, where information about the material, such as a special material number, the supplier and the number of pieces on a pallet are shown. The second part is a barcode which, if scanned, reveals all the information that is also displayed on the Kanban card. All the pallets are stored temporally before they are distributed among the production area.

The production area at the Deventer plant consists of four production lines. One main line, which is a conveyer belt that runs through the factory and three smaller standalone production lines, where workers have to pass the heating boilers manually. These lines are all different in the way that each production line has its own workers and working hours. It can happen that the workers at one production line work 6 hours a day and the other ones 8 hours. Even the number of shifts can vary between one or two shifts a day. Each production line is divided into sections. Each section assembles its own part to the cascade of the heating boiler. So each section needs its own materials, which have to be delivered to them by the workers of the department of internal logistics.

Each section has a box where all empty Kanban cards are collected. Every 15 minutes a worker of the internal logistics department makes a round passing by every section at the production area collecting the Kanban cards from the collection boxes. At the same time this worker delivers the material that was stored temporally, to each section. When the worker is finished making his round, he scans all the Kanban cards that he collected. The information that is associated with the barcodes on the Kanban cards is recorded in the Enterprise Resource Planning (ERP) system. For each order, data from the ERP system is used to make a list of materials and amounts that needs to be ordered. This list is made in the following way: Every time a Kanban card is scanned, the corresponding material and amount is stored together with the supplier. Hereby, each material has its unique supplier. At the time an order has to be placed at a supplier, a worker extracts a list with the materials and amounts corresponding to all the Kanban cards from the correct supplier that were scanned in the ERP system. This list is send to the supplier and the materials and amounts are removed from the ERP system, such that those materials are not ordered again until the corresponding Kanban card is scanned again.

The total amount of materials on the order should not exceed the capacity of truck. Might it be case that the total amount of materials does exceed the capacity of one truck, a special extra truck has to deliver the remaining amount. This not only jeopardizes the assembly of heating boilers due to an increased chance on a standstill in production, but also costs more than a standard truck. This means that selecting the moments an order is send is crucial.

1.4. Overview

This subsection gives an overview of the structure of this thesis. To answer the questions of the problem statement, a model is developed, which is called the Integrated Supply Model (ISM).

In the next section, the developed Integrated Supply Model is described. This is divided into several parts. The first part is about delivery process of the materials. The second part describes the order process of the materials. The third part is about the scheduling of the trucks. After that, a subsection is devoted to the Kanban process, which is used to specify the quantities of materials that are ordered. The latter is determined with help of the Kanban system, discussed in section 1.3. The main problem that has to be tackled in the order process, is that the orders do not exceed the capacity of the truck, while in the truck arrival scheduling process the main problem is the limited number of docks to unload the trucks. The Kanban process incorporated in the Integrated Supply Model must ensure that the production does not come to a standstill.

In the third section, two approaches are described to solve the Integrated Supply Model. The approaches are different by making different assumptions, which are explained in that section. After that, the limitations and potential of the two approaches are discussed. Finally, the model of one of the two approaches is improved for the implementation at the Deventer plant. This improved model is also discussed.

In the fourth section, the implementation and results of both approaches are discussed. Next to that, the implementation and results of the improved model are presented. First, the input and output of the two models for the two approaches are given. After that, the results for those two models are given. Furthermore, the results of the improved model are given and compared to the other models. Moreover, the improved model is used for a real world implementation. The adaptions due to this real world implementation are given next. Finally, the results of the improved model implementation in the real world situation are given.

In the fifth section, other production control methods as the Kanban system are researched. A comparison is made to investigate if another production control method would make the improved model perform better. In the sixth section, the conclusions are given and a discussion is held what further research could add to benefit Bosch.

2. Integrated Supply Model

In this section the Integrated Supply Model (ISM) for solving the Bosch supply problem is explained. The ISM coordinates the determination of the arrival times of the trucks and the composition of the orders. With help of the ISM the questions of the problem statement can be answered. The ISM is divided in separate parts, each of which covers a different part of the Milkrun system, explained in the previous section. First the delivery of materials is discussed and then the order process is considered. After that, the scheduling of the trucks at the dock is covered. This concludes the timing of placing the orders. The remainder of this section is dedicated to specify the quantities that are assigned to an order. These quantities are determined with help of the Kanban system described in the previous section. This section ends with a summary of the Integrated Supply Model and gives an insight how the ISM is solved.

Before the different processes are explained in more detail, the notion of an order is defined more precisely: An order i consists of a list of materials $\mu_1, \dots, \mu_m$ and their corresponding amounts $\alpha_1^i, \dots, \alpha_m^i$. The assumption is made that each material μ_j has a unique supplier and all the materials of an order have to have the same supplier. The supplier belonging to order i is denoted by s_i. As a consequence of these assumptions, each order is send to only one supplier. Furthermore, the amounts of the order have to be such that the total order can be delivered by one truck.

2.1. Delivery process

In this subsection, a more detailed description is given of the delivery process. Furthermore, the concerning restrictions are discussed.

A delivery is triggered by an order i that is send to the corresponding supplier s_i. The moment that order i is send to the corresponding supplier is called the "Call off Point", denoted by CoP_i. After a Call off Point the corresponding supplier processes the order. This means that the required materials are picked such that those materials are ready to be loaded into the truck. At the moment that a truck of the transporting company, HSL, arrives at the supplier, the materials are loaded into the truck. That truck delivers the materials directly to the Deventer plant. Depending on if there is another truck that uses the dock at that moment or not, the oncoming truck either has to wait until the dock become free or can directly start to unload the materials. The possible waiting time of the truck at the Deventer plant is denoted by Δ_w. The goal is to reduce this waiting time to zero by scheduling the trucks in a smart way.

If the dock is free, the truck starts unloading the delivery of order i. This time is denoted by UT_i. After the unloading of the truck the materials are distributed to the designated areas in production. This is done by the same workers that unloaded the truck. The unloading of a truck and the distribution to the production areas takes about 45 minutes. This means also that during that time no other trucks can unload their materials. The moment that all the materials of order i are distributed among the production area is denoted by EP_i. The times UT_i and EP_i are related by the following equation:

$$EP_i = UT_i + 45\ min \tag{2.1}$$

The time that it takes to deliver the materials to the Deventer plant is called the delivery time. It is defined as the time from the Call off Point until the time that the truck begins unloading the materials. The minimum delivery time is the least amount of time that it takes to deliver the materials to the Deventer plant and is denoted by Δ_d. Due to a positive waiting time or due to a chosen strategy, the real delivery time can be longer than the minimum delivery time. Hence, the waiting time can be a part of delivery time. This leads to (2.2).

$$UT_i \geq CoP_i + \Delta_d \tag{2.2}$$

An overview of the delivery process is given in Figure 2.1. It shows a time line where the delivery process from the Call off Point to the moment the truck is finished unloading the materials are displayed. There is a difference between the arrival of the truck at the Deventer plant and the moment the truck starts unloading, namely the waiting time Δ_w. Despite of this difference, in the following every time the arrival of the truck is mentioned, the waiting time is omitted, such that the arrival of the truck and UT_i are at the same time. In the next subsection, the order process is explained in more detail and the restrictions concerning the order process are given.

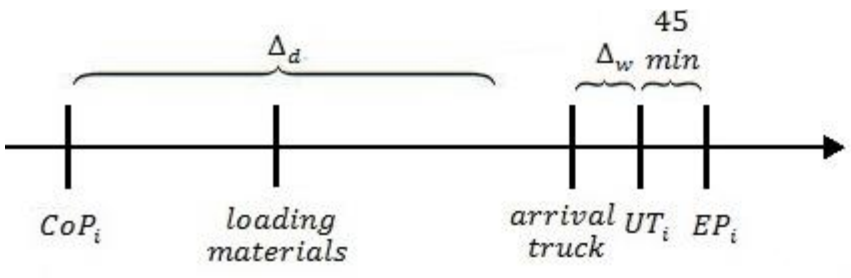

Figure 2.1: Time line of the delivery process

2.2. Order process

In this subsection, a more detailed description is given of the order process. Furthermore, the restrictions concerning the order process are discussed. The order process is the process from the moment that the material is being used until the order is send to the supplier, the Call off Point. First, the process is explained for a single order. After that, the order process of consecutive orders for the same supplier is discussed.

At the Call off Point, the order is send to the corresponding supplier, but before that can be done, the order has to be filled. As mentioned in the previous section, Bosch uses an Enterprise Resource Planning (ERP) system to record the materials that are being used in production. This is done with help of the Kanban system, which is explained later in this section. The order is filled with all the materials from which the Kanban card is recorded in the ERP system before the Call off Point and which have not been processed by a previous order. Note that this is not the same as the amount of materials that are being used until the Call off Point due to the following reason: As discussed in the previous section, after a material is being used, the corresponding Kanban card is put into a collection box. But there is a certain amount of time which passes before a worker of the department of internal logistics has scanned the Kanban card.

Only then, the ERP system records that the material is being used. The maximum amount of time between the moment a material is being used and the moment the corresponding Kanban card is scanned, is denoted by Δ_k.

The above has the consequence that the materials that are being used after $CoP_i - \Delta_k$ may go on the next order, because the corresponding Kanban cards may not be recorded into the ERP system before the Call off Point. In the following, we assume that the time $CoP_i - \Delta_k$ is the separation point between two consecutive orders, meaning that all material used until this time is assumed to be processed by order i. Hence, from this point in time, the materials used in production are assumed to be processed by order $i + 1$. This point is time is called the start point of an order. At the same time, this is also the end point of the previous order. The start point of order i is denoted by SP_i. Shifting the above to get the equation for SP_i leads to the following:

$$SP_i = CoP_{i-1} - \Delta_k \tag{2.3}$$

An overview of the order process is given in Figure 2.2. It shows a time line where the order process of order i from the start point of the order to the moment the truck is finished unloading the materials are displayed. Note that the end point of order i is equal to the start point of order $i + 1$.

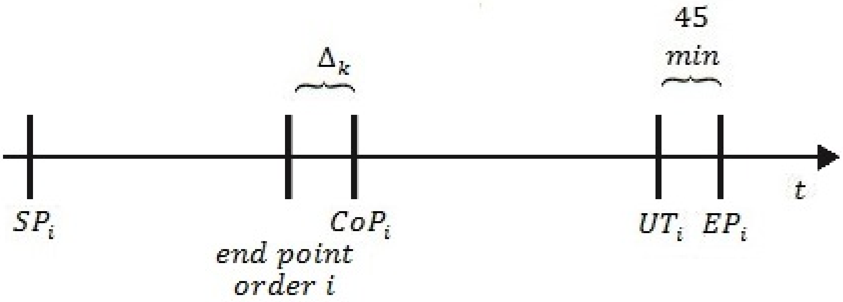

Figure 2.2: Time line of the order process

Multiple orders

In the above, the order process of a single order was described. In the following, several consecutive orders for the same supplier are considered.

The order has a starting point and an end point. All materials recorded into the ERP system in between these times for the corresponding supplier go on that order. Furthermore, the end point of the current order is the same as the starting point of the next order. More formal, this means that materials that are recorded into the ERP system between SP_i and SP_{i+1} go on order i. The time between two starting points is called the Call off window. In Figure 2.3, a time line is shown with two Call off windows. Note that the order can only be send if the corresponding Call off window has passed, otherwise the order is send to the supplier before the order is filled completely.

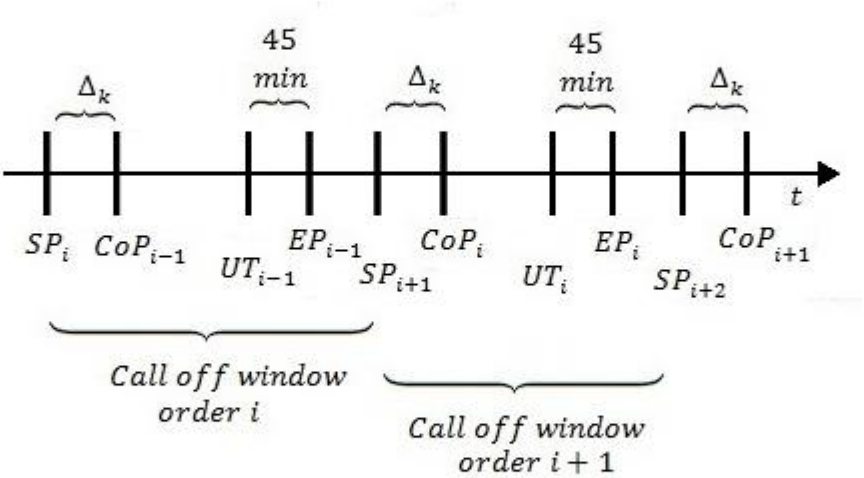

Figure 2.3: Time line of the order process of multiple orders

2.3. Scheduling trucks

In the previous subsections the order and delivery processes were described. To ensure that the trucks do not arrive at the same time, their arrival times must be regulated. In this subsection the process of scheduling the trucks at the Deventer plant is discussed.

At the moment the truck arrives at the Deventer plant to deliver the materials, the truck could start to unload. This takes 45 minutes and within this time no other truck can unload materials at the Deventer plant. This is because there is only one dock present at the Deventer plant for unloading these materials and the truck that is being unloaded uses this dock completely. Hence, the dock is occupied for 45 minutes after a truck starts to unload materials. Based on the above, within the Integrated Supply Model timeslots of 45 minutes can be used. The reduction to a limited and quite small number of timeslots reduces the number of solutions to the scheduling problem for the unloading of the trucks. In the following the i-th timeslot is expressed as T_i.

Within the ISM, only the trucks of HSL are being scheduled. However, not all possible timeslots may be available for the trucks. This can be due to the opening hours of the suppliers, the lunch break of the workers in the department of internal logistics or due to an arrival of a truck of Veenstra. This results in a list of timeslots that are blocked and only the remaining timeslots are available for the trucks of HSL to deliver the materials. Possible approaches to schedule the trucks of HSL described in the Section 3. An important restriction is that the trucks of one supplier must arrive in the same sequence as the orders are sent to the suppliers. This means that the truck corresponding to order i arrives earlier than the truck corresponding to order $i + 1$. This leads to (2.4).

$$UT_i < UT_{i+1} \tag{2.4}$$

The timeslots are illustrated in Figure 2.4. In part a), the timeslots are shown without restrictions. In part b) the blocked timeslots are colored red and in part c) the timeslots where the trucks are scheduled are added in green.

As mentioned earlier, the trucks are scheduled following one of the approaches described in the next section. However, for this schedule, it remains to specify how the Call off Points are determined as they determine the amount of materials that is on the corresponding order. Hereby is important that the total amount of materials has to fit into one truck. In the next subsection more details on this process is given.

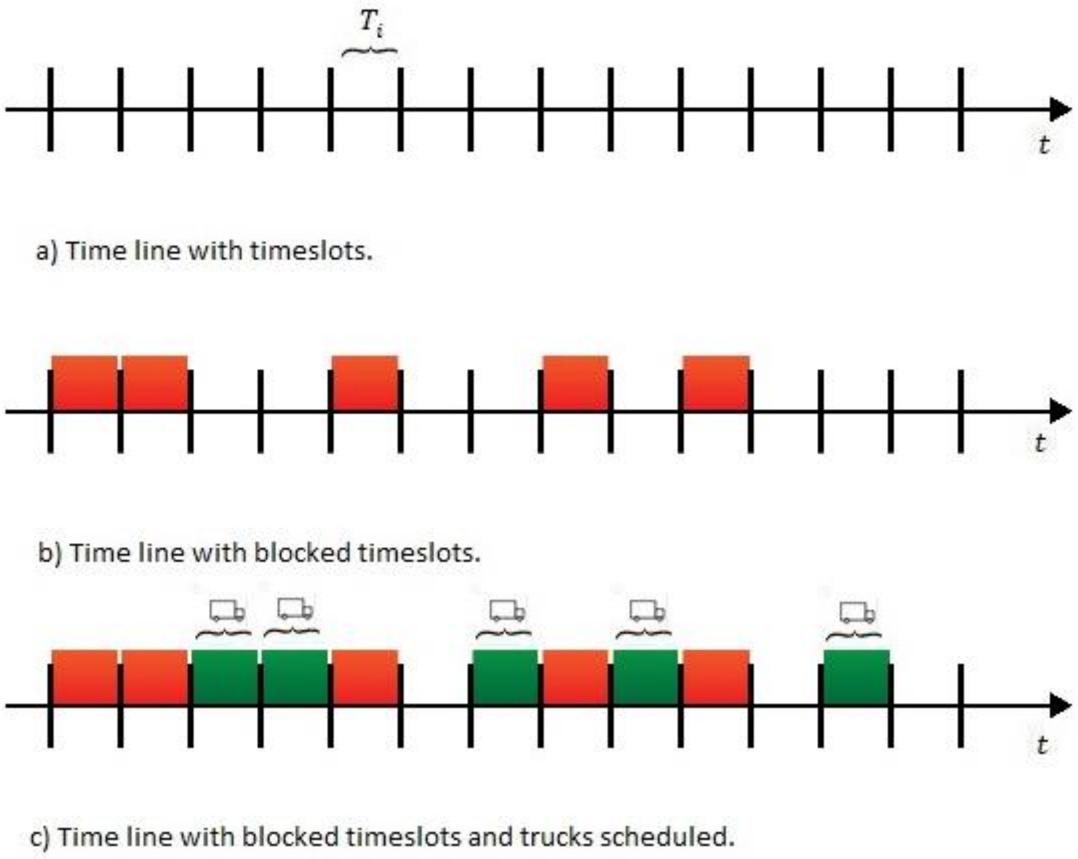

Figure 2.4: Time line with timeslots

2.4. *Kanban process*

In the previous subsections the timing of an order has been described. It remains to specify which quantities are assigned to an order. Hereby it is important that the amount of materials on an order must be such that it does not exceed the capacity of the truck. Furthermore, the production must not come to a standstill. In this subsection, first the method to measure the space that materials take up in a truck is explained. After that, the capacity restriction is formulated. Then, the method to ensure that the production does not come to a standstill is discussed and the accompanying restrictions are formulated. An important factor to ensure this is the number of Kanban cards available in the system. At the end of this subsection, first the replenishment time is explained and afterwards the other factors that are needed to determine the number of Kanban cards are discussed. Finally, the calculation of the number of Kanban cards is discussed in more detail.

The start points of the Call off windows must be chosen such that the total amount of materials in the corresponding Call off windows fit into one truck. The space in a truck is expressed in floor places, which is the space one pallet takes up. To measure if the total amount of materials does not exceed the capacity of the truck, the floor place index is used.

The floor place index states how many floor places one piece of a material takes up in a truck. Hereby it has to be taken into account that, for some materials, the pallets can be stacked on top of each other, depending if the material is rigid enough. For example if 4 pieces of material j go on one pallet and 2 pallets can be stacked on top of each other, one piece of material j has a floor place index of $1/8$.

The number of floor places an amount α_j of material j with floor place index fp_j takes up, is denoted by $fp_j(\alpha_j)$ and can be calculated by $fp_j(\alpha_j) = \alpha_j * fp_j$. This is not rounded up, because the different materials can be stacked on top of each other. The capacity of a truck, CAP, is also expressed in number of floor places. For each order, the total number of floor places that all the materials on that order take up, must be less than the capacity of the truck. If $\alpha_j^i, \dots, \alpha_m^i$ denotes the ordered quantities on order i, this leads to the following constraint:

$$\sum_{j=1}^{m} fp_j(\alpha_j^i) \leq CAP \tag{2.5}$$

Constraint (2.5) discusses the capacity restriction of the quantities that are assigned to an order. The other restriction is that the production must not come to a standstill. To ensure this, it is important to know the quantities of materials that are used in production. With these quantities, the amount of materials that must be ordered such that the same inventory level is maintained, can be determined.

Denote by $q_j(t)$ the quantity of materials used in production at moment t and let the amount of material j that is used in production between two moments in time t_1 and t_2 be denoted by $Q_j([t_1, t_2])$. Then the following is true:

$$Q_j([t_1, t_2]) = \int_{t_1}^{t_2} q_j(t)dt \tag{2.6}$$

Let the inventory level of material j at moment t be denoted by $I_j(t)$. The materials that are on order i are delivered to the Deventer plant at UT_i. 45 Minutes later all the materials are delivered to the corresponding section at the production area. At that moment, denoted by EP_i, the inventory levels are restocked. The next moment that the inventory levels get restocked is at EP_{i+1}. In between those moments the inventory levels only decreases due to the quantity of materials that are used in production. Because the production comes to a standstill if the inventory level of any material becomes zero, the following constraint ensures that this does not happen:

$$I_j(EP_i) \geq Q_j([EP_i, EP_{i+1}]) \quad \forall i, j \tag{2.7}$$

To record the quantities of materials that are being used in production, Bosch uses the Kanban system as discussed in Section 1.3. The Kanban system works with Kanban cards that record the materials that are being used and must be ordered again. The quantities α_j^i of material j on order i are the materials that are being used between SP_i and SP_{i+1}. This is expressed in (2.7):

$$\alpha_j^i = Q_j([SP_i\,, SP_{i+1}]) \tag{2.8}$$

Note that SP_{i+1} is not a moment in the future since it lies before CoP_i , the Call off Point of order i , as shown in Figure 2.3. This means that the Kanban system is based on quantities of materials that are used in the past instead of in the future. A consequence of this is that first, a material has to be used before it is ordered, while the expression of (2.7) is based on ordering the materials that are needed in the future.

The above leads to a problem, which can be explained using Figure 2.5. In this figure the quantity of materials used in production during some time period are given and the red line indicates the end point of order i. Note that this is the same as the start point of order $i + 1$. As the amount of materials used in production changes strongly at this Call off Point, a problem may occur. All the materials used during the green period are reordered within order i, but the production needs all the materials used within the yellow period to produce all the required heating boilers. Obviously, this may lead to a standstill if the inventory levels are not high enough to cope with this increased quantity of materials.

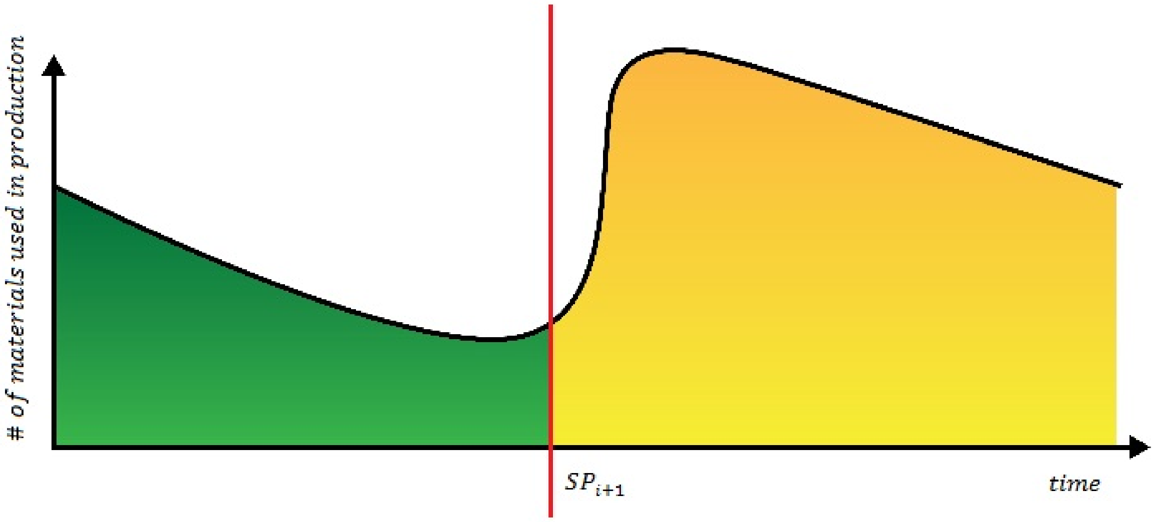

Figure 2.5: The problem of the Kanban system

To avoid problems like the one mentioned above, the inventory levels must be higher. This leads to higher holding costs and requires much space to store the materials. Another option is that the Kanban system is only used if the quantities that are used in production do not change too much. In Section 5 some other systems for production control methods are reviewed to overcome this problem.

Replenishment time

Although the Kanban system is based on the materials used in the past, a proper choice of the number of Kanban cards per material can ensure that the inventory levels remain high enough to prevent a standstill in production. For determining this number of Kanban cards, the replenishment time is important. It measures the time that it takes to order and deliver the materials. The replenishment time is recorded from the moment a material is used in production until the material is delivered to the same section in production.

Measuring the replenishment time exactly for each material individually is often difficult and therefore the maximum replenishment time is taken for each order. This maximum replenishment time of order i, denoted by RT_i, is given as the time between SP_i and EP_i. Hence, it measures the first possible time that a material, that is on order i, is used in production and it ends with the time that all the materials are delivered to the corresponding section in production. This leads to:

$$RT_i = EP_i - SP_i \tag{2.9}$$

In Figure 2.6, the replenishment time is shown. This figure shows the same time line as in Figure 2.3. Note that during the replenishment time, both the truck of order i as well as the truck of order $i - 1$ arrives to deliver materials.

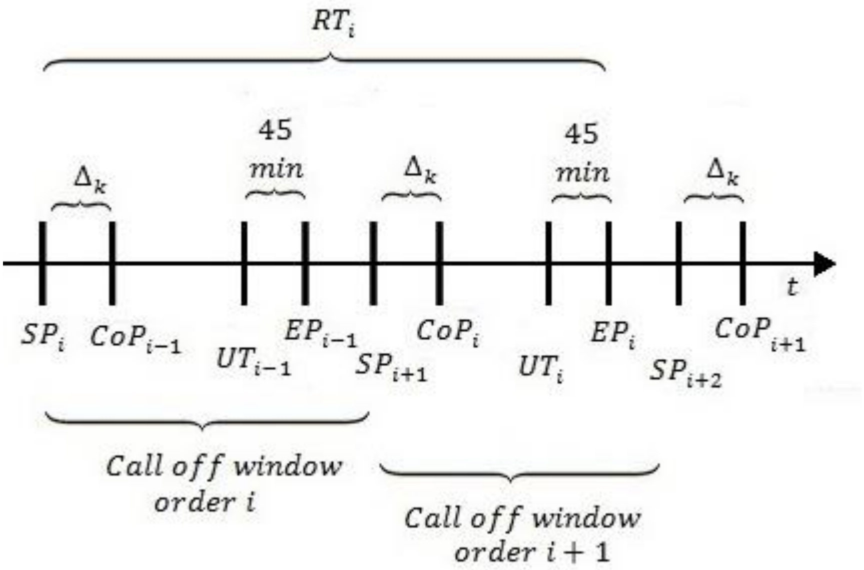

Figure 2.6: Replenishment time

Number of Kanban cards

At Bosch, the number of Kanban cards per material is determined each week. The amount of Kanban cards is compared with current amount of Kanban cards and more Kanban cards are made as necessary. A couple of times per year a certain number of Kanban cards are removed from the system. It is important however that the number of Kanban cards is calculated with precision, because otherwise too many or too few Kanban cards are monetized.

The determination of the number of Kanban cards is discussed in this subsection. However, first the importance of the Kanban cards is explained.

The Kanban card is an important factor in the Kanban system. Without these cards, no materials are ordered. Every time all the materials on a pallet are used, the corresponding Kanban card is send to the department of internal logistics to order those materials. The number of Kanban cards per material is essential to prevent that the production comes to a standstill. When there is only one Kanban card, there will be a standstill when all the materials on the pallet corresponding to that Kanban card are being used. Hence, there should always be another Kanban card for the same material in the inventory, such that the materials on the pallet corresponding to the second Kanban card can be used in production. However, if there are too many Kanban cards of a material in circulation, the inventory level of that material becomes too high. As a consequence, the holding costs are higher and more space is needed to store all the materials.

Depending on four factors that influence how much Kanban cards are needed per material, the number of Kanban cards differs. These factors are the demand per day, the minimum order quantity, the replenishment time and the number of working hours per day. The first factor is the demand per day d of material j, denoted by D_j^d. In the Integrated Supply Model, this is equal to the quantity of materials that is used in production during day d. If the demand is high, there are more Kanban cards needed than if the demand is low, because the materials deplete more quickly and thus, a higher inventory level is needed. The maximum is taken over all the days of the week. The maximum demand of material j per day, denoted by D_j, is:

$$D_j = \max_d D_j^d \tag{2.10}$$

The next factor is the minimum order quantity of material j, denoted by MOQ_j. This is the amount per Kanban card. If the minimum order quantity (MOQ) is low, there are more Kanban cards needed than if the MOQ is high, because a low number of materials can be ordered, the inventory runs out more quickly. The third factor is the replenishment time, as discussed earlier. If the replenishment time is high, there are more Kanban cards needed than if the replenishment time is low. The last factor is the working hours per day of material j, denoted by W_j. This is the number of hours per day that material j can be used for production. This depends on the production line(s) at which the material is used. The working hours are used to scale the replenishment time such that only relevant hours are measured.

The number of Kanban cards of material j needed for order i, denoted by K_j^i, is based on the quantity of materials that are used in production during the replenishment time, that is from SP_i until EP_i. The actual number of Kanban cards is achieved from this quantity by dividing it by the number of materials per Kanban card, MOQ_j:

$$K_j^i = \int_{SP_i}^{EP_i} q_j(t)dt \,/MOQ_j \tag{2.11}$$

Remember from (2.6) that the integral from (2.11) is equal to $Q_j([SP_i, EP_i])$. The actual number of Kanban cards of material j needed to prevent running out of material j, denoted by K_j, is the maximum number of Kanban cards over all orders:

$$K_j = \max_i K_j^i \tag{2.12}$$

The problem with these calculations is that SP_i, EP_i and $q_j(t)$ vary on a daily basis. To overcome this, an approximation is used. An upper bound is chosen for the determination of the number of Kanban cards. This upper bound is also used by Bosch and is described by Y. Sugimori et al. in [SKCU77].

For the upper bound of (2.12), the replenishment time, R_j, is taken as the maximum replenishment time of all orders of the next week consisting of material j:

$$R_j = \max_{\{i|j\in i\}} RT_i \tag{2.13}$$

The number of Kanban cards of material j, denoted by K_j, is now calculated in the following way:

$$K_j = \frac{D_j}{MOQ_j} * \frac{R_j}{W_j} + 1 \tag{2.14}$$

The four factors in (2.14) are consistent with observations made above about the number of Kanban cards. Furthermore, the term $\frac{D_j}{MOQ_j}$ is number of Kanban cards of material j per day. The term $\frac{R_j}{W_j}$ is the number of replenishments per day. The resulting number of Kanban cards, K_j, is corrected with a safety factor which ensures that there are enough Kanban cards such that the production certainly does not come to a standstill.

2.5. Overview

In this subsection a summary is given of what is discussed in this section and is explained how to solve the model. In the first subsections, the timing of the order and the truck arrivals were discussed. The delivery process was elaborated first, in which the process from the moment the order is placed until the moment the materials are delivered to the sections in production was explained. Secondly, the order process was considered. Here, the process from the moment the material is used in production to the moment the order is placed was discussed. In the third subsection, the scheduling of the trucks was explained. After that, the quantities of the orders were specified. In that subsection, both the capacity restriction as well as the restriction that the production must not come to a standstill were dealt with. For the latter restriction, the number of Kanban cards has to be determined, which was discussed in that subsection.

In the Integrated Supply Model three decision variables are present: The Call off Point, the moment of the truck arrival and the number of Kanban cards. The Call off Point must be chosen such that the order does not exceed the capacity of the truck. The moment of the truck arrival must be chosen such that the truck delivers materials at a time when the workers at the Deventer plant can unload the truck. If the number of Kanban cards is fixed, an upper bound of the replenishment time can be determined.

If two of these decision variables are known, the third can be calculated. If the Call off Point and the moment of the truck arrival are known, the replenishment time can be calculated. With the replenishment time, the number of Kanban cards can be determined.
If the number of Kanban cards is known, the maximum replenishment time can be calculated. If the Call off Points are also determined, the upper bound on the arrival times can be calculated by adding the maximum replenishment time to the Call off Points. This moment is an upper bound of the time that every material is delivered to the section at the production area. Thus, if for order i, CoP_i is known, an upper bound of EP_i can be determined and from (2.1) it is known that $UT_i = EP_i - 45\ min$. If the arrival times of the trucks are known instead of the Call off Points, the lower bound of the Call off Points can be determined by reversing the above calculations.

In the next section two approaches are explained, based on these decision variables. The first approach determines the times at which a truck should ideally deliver the material. This ideal moment is when the truck has a full load. If the truck cannot deliver the materials at that moment, another less ideal moment is determined. After fixing the arrival time, the Call off Point is fixed as Δ_d before the truck arrival time.

The second approach determines the next Call off Point as the last moment for which the capacity of the truck is not exceeded. If this ideal Call off Point is reached, the truck delivers the corresponding materials as soon as possible after the Call off Point, accounting for the moments when the truck cannot deliver materials to the Deventer plant.

With both approaches, the number of Kanban cards is determined such that the inventory level is high enough to prevent a standstill in production. This means that with these approaches the number of Kanban cards is dependent on the Call off Points and the moments the trucks deliver the materials. In the next section both approaches are explained in more detail.

3. Approaches

In the previous section, the Integrated Supply Model for solving the Bosch supply problem was explained. In this section two approaches for solving the supply problem are explained. The first approach focusses on the arrival of the trucks. The Call off Points are determined based on the truck arrivals, which are chosen as close to the ideal moment as possible. The second approach focusses on the Call off Points. Based on those chosen moments, the moment that the corresponding truck delivers the materials are determined. With both approaches the third decision variable, the number of Kanban cards, is determined based on the chosen Call off Points and truck arrivals. In this section, first the current approach for scheduling the trucks that deliver great volume materials is explained. Then, the assumptions for the ISM are discussed. After that, both approaches are explained. The limitations and potentials of both approaches are discussed next and finally one of the two approaches is extended to the Extended Integrated Supply Model (EISM).

3.1. Current Approach

Before explaining the two approaches developed to optimize the supply chain of Bosch, the current approach for ordering great volume materials is shortly discussed.

This approach predicts, for each day of the week, the number of trucks that are needed to deliver all the materials per supplier. The prediction is made on the basis of the production planning. The number of trucks is calculated with help of the floor place index. The day with the highest number of trucks is taken. This process is done for all suppliers such that for each supplier is known how many trucks are needed at most per day. These numbers of trucks are then used for every day of the week implying that there are always enough trucks to deliver the materials. This is done each week when a new production plan is made for the next week.

This approach obviously uses many trucks. To reduce the number of trucks, two new approaches are developed. Both approaches make use of the Integrated Supply Model described in the previous section. Before the two approaches are explained, the assumptions made are elaborated.

3.2. Assumptions

In this subsection the relevant assumptions are discussed. First, the use of the timeslots is discussed. Furthermore, the assumption is made that the predicted amount of materials used in production is equal to the actual quantity of materials that are used in production. The last assumption that is discussed in this subsection is about a safety margin to prevent that the capacity of the truck is exceeded.

In Section 2.3, the scheduling of the trucks was discussed. In that section timeslots were mentioned and it was assumed that the Integrated Supply Model uses timeslots of 45 minutes. This coincides with the time that the dock is occupied by an unloading truck. The use of timeslots is not only necessary for scheduling the trucks, but also for the Call off Points and the time windows to measure the quantity of materials that are used in production. If we chose to use also timeslots of 45 minutes for these points, a limited and quite small number of timeslots is obtained. In a first step, the reduced solution space has to be chosen to be the solution space for the Integrated Supply Model. In the Extended ISM, the length of the timeslots is reduced to 15 minutes. This is done to have a better prediction of the quantity of materials that are used in production. As a consequence, the occupancy of the trucks will get higher.

The next assumption is about estimating the quantity of materials used in production. Due to agreements with HSL, the truck schedule for the whole week must be send to HSL at the end of the previous week. This truck schedule specifies a schedule of all trucks of HSL with the times when the trucks have to pick up the materials at the supplier and the times that the truck must deliver the materials at the Deventer plant. This schedule is fixed and cannot be changed during the week. As a consequence of this schedule, the Call off Points and the moments the trucks arrive must be determined a week in advance. Hence, the actual quantity of materials used in production cannot be used to determine the decision variables. Instead, a prediction has to be used to estimate the quantity of materials. This prediction is based on the production planning made a week in advance.

The production planning specifies for each day of the week the quantities of materials that are planned to be used for the production at that day. These values are calculated based on the number of production lines and the number of shifts in production. The Integrated Supply Model uses this information as input. It determines per timeslot the quantity of materials used in production by spreading the specified quantities evenly over the hours that the material is being used within the planned production scheme. Note that this number of hours can differ per material depending on the production line at which the material is used. Spreading the used materials evenly over the day is not completely accurate. The reason for this is that at some production lines multiple types of heating boilers are made. Within this mix it might occur that some types are produced more at the beginning of the day. As a consequence, the materials needed for the production of that type of heating boiler are used first, instead of that it is spread out evenly over the day.

The total quantity of materials used in production per timeslot is used to determine the Call off Points and the moments that the truck arrive at the Deventer plant. The method to determine this total quantity is shown in Figure 3.1.

As already mentioned, the prediction of the used amount of materials is not exactly the same as the actual use of materials. Next to the differences resulting from the mix at the production lines, also backlog or other unforeseen difference in production can lead to deviations. Another reason that the prediction is not accurate is because the usage of materials is a continuous process, while scanning the Kanban cards is not. As a consequence, there is some noise around the Call off Points. The difference between the predicted quantity of materials and the actual use of materials might cause that some Kanban cards that should, based on the planning, have been on the current order, are on the next order. In that case, the occupancy of one truck is slightly less, while the occupancy of the next truck is slightly more. To prevent that the actual occupancy is more than 100%, a safety margin is introduced.

The safety margin is denoted by $\gamma \in [0,1]$ and specifies the fraction to which a truck may be filled in the planning. This means that the Call off Points are determined such that the truck should not be occupied more than $1 - \gamma$ times the capacity of the truck. When the truck is filled with the actual quantity of materials, the safety margin leaves space to cope with differences between the predicted and actual quantity of materials. In this way, all the materials still can be delivered in one truck to the Deventer plant.

This leads to the following constraint:

$$\sum_{j=1}^{m} fp(\alpha_j^i) \leq CAP * (1 - \gamma) \tag{3.1}$$

In the next subsections, the two developed approaches are explained, but before that, the method to predict the quantity of materials used in production for each supplier is explained in more detail. The predicted quantity of material j of supplier s between timeslots t_1 and t_2 is denoted by $PQ_j^s([t_1, t_2])$. At each timeslot, the quantity of materials used from the first relevant timeslot until the current timeslot is calculated per material. This is used to determine the total quantity of material. The quantity of materials is expressed in number of floor places. The total number of floor places of the materials used in production of supplier s until timeslot t is denoted by TF_t^s. This process is shown in figure 3.1.

$For\ Supplier\ s = 1\ to\ LastSupplier\ S$

$\quad For\ TimeSlot\ t = 1\ to\ LastTimeSlot\ T do$

$\quad\quad For\ Material\ j = 1\ to\ LastMaterial\ m\ do$

$\quad\quad\quad Update\ \alpha_j \coloneqq PQ_j^s([1, t])$

$\quad\quad End\ For$

$$Update\ TF_t^s \coloneqq \sum_{j=1}^{m} fp(\alpha_j)$$

$\quad End\ For$

$End\ For$

Figure 3.1: Method to determine quantity of materials used in production

3.3. Approach 1: Determine truck arrivals

In this subsection the first approach is explained. This approach focusses on the arrival of the trucks. The Call off Points are determined based on the moments that are chosen for the trucks to deliver the materials.

The moment a truck can start to unload the materials at the Deventer plant, UT_i, is derived using the Call off Point, CoP_i, and the minimum delivery time to deliver the materials to the Deventer plant, Δ_d. Remember from formula (2.2) that these times are restricted by $UT_i \geq CoP_i + \Delta_d$. This means that the truck corresponding to order i, that is send to supplier s, must arrive at least Δ_d time later than the time that order i is placed. However, if the timeslot for UT_i is determined first, this constraint tells us that the Call off Point must be at least Δ_d before UT_i.

In Approach 1, the Call off Point is set exactly Δ_d before UT_i:

$$CoP_i = UT_i - \Delta_d \quad \forall i \tag{3.2}$$

As the goal should be to have the trucks loaded as close as possible to their capacity, it still should be the goal to schedule the next Call of Point as close as possible to the preferred next Call of Point. This implies that the used arrival time of the truck, UT_i , should be as close as possible to the truck arrival time which follows from the preferred Call of Point. Because of (3.2), this means that the Call off Point must be shifted backwards in time such that the truck arrives within a timeslot that is available.

It remains to specify how precisely the backward shifting is realized. Before that can be done, the approach is explained in more detail. For each timeslot, the method of Figure 3.1 is used to determine the total number of floor places used until the current timeslot. A matrix M is constructed, where $M_{i,j}$ specifies when the truck should ideally arrive at the Deventer plant for each supplier i when the last Call off Point was at timeslot j. This matrix is filled as follows: For position $M_{i,j}$, the total number of floor places of supplier i at timeslot j is used as starting point. Let p be a counter starting at zero that goes up by one every time constraint (3.3) is not violated.

$$TF_{p+1}^{i} - TF_{j}^{i} \leq CAP * \gamma \tag{3.3}$$

Eventually, this means that $p + 1$ is the first number that would violate the restriction of (3.3). As a consequence, p is the timeslot at which the truck would be as full as possible. The truck corresponding to the Call off window from timeslot j to p would arrive Δ_d later, due to the assumption of this approach. Hence, the position $M_{i,j}$ is filled with $p + \Delta_d$, the timeslot for which the truck from supplier i arrives at the Deventer plant with a maximum load, if the previous Call off Point of supplier i was at timeslot j. In Figure 3.2, an example of the matrix M is shown.

M(i,j)	1	2	3	4	5	6
HSV	12	12	12	12	14	15
Intermeco	27	27	27	27	31	32
Lentink	12	12	12	12	19	20
Timmerije	55	55	55	55	58	60

Figure 3.2: An example of the matrix M(i,j)

Beginning at the start of the planning horizon, the moments that the trucks arrive at the Deventer plant are determined for each supplier. These moments come from the matrix M. The first timeslot is determined by checking position $M_{i,1}$, the next Call off Point is Δ_d earlier than the timeslot shown at position $M_{i,1}$, k. For the next truck, position $M_{i,k-\Delta_d}$ has to be checked and so on. All these timeslots for the arrival of the trucks are recorded as possible timeslots, because it is not sure that the trucks can arrive at the Deventer plant at that timeslot.

If all the trucks can be scheduled at these possible timeslots such that it results in a feasible schedule, this would lead to a schedule where the trucks are all as full as possible. But in this scheduling problem, it is possible that the assigned possible timeslots are already blocked due to lunch breaks, opening hours of the supplier or the arrival of a truck of Veenstra. If, due to a blocked timeslot or by an already scheduled truck, another truck could not arrive at the assigned possible timeslot, it can only arrive earlier than the ideal timeslot. Otherwise, the corresponding Call off Point would be later, which means the capacity of the truck would be exceeded. The timeslot that is chosen for the arrival of that truck is the first timeslot that is closest to the ideal timeslot without violating constraint (3.1).

If a truck must arrive earlier, due to the fact that the ideal timeslot is blocked, the corresponding Call off Point is not the only thing that changes. All the possible timeslots from the same supplier has to be determined again. Another problem that arises with the Integrated Supply Model becomes apparent when the transition has to be made between the weeks. If a truck has to arrive Monday morning, the order has to be sent the previous week. The ISM cannot cope with this. To overcome this problem, a restriction is introduced that ensures that the last truck of each supplier arrives at the Deventer plant Friday afternoon.

The scheduling problem that describes this problem is defined as follows: For each supplier i, let us define a vector of Call off Points $c_1^i, \dots, c_{n_i}^i$ with n_j the number of Call off Points of supplier i. For these c_k^i the following restriction must hold to ensure that the capacity restriction of the truck is not violated:

$$m_{i,c_k^i} \geq c_{k+1}^i + \Delta_d \tag{3.4}$$

Furthermore the last truck of all suppliers must arrive at the Deventer plant after a predetermined boundary, L:

$$c_{n_i}^i \geq L \tag{3.5}$$

All the Call off points c_k^i must be disjoint and must be unequal to a blocked timeslot. The aim is to find for all suppliers i a sequence as specified above, where $\sum n_i$ is minimized. That is, minimize the total number of trucks.

This scheduling problem can be easily formulated as an Integer Linear Program (ILP), which is solved by the optimizing software called AIMMS. In the next section, the input and the implementation for this ILP is described.

3.4. Approach 2: Determining Call off Points

In this subsection the second approach is discussed. This approach focuses on the Call off Points. The Call off Point is determined first and after that the earliest timeslot that is available for the arrival of the truck is determined.

In the first approach, the delivery time was set to the minimum delivery time. By doing this, a problem arose if the truck could not deliver the materials at the preferred time. In that case, the timeslot of the truck arrival as well as the timeslot for the Call off Point was shifted backwards. This resulted in a smaller Call off window, what meant lower occupancy in the truck. The second approach solves this problem by fixing the Call off windows and shifting the timeslot that a truck can deliver the materials forwards instead of backwards.

For this approach a matrix N is constructed. This matrix records when the Call off Points ideally has to take place for each supplier i and timeslot j. These Call off Points are determined in a similar way as for the matrix M. Let p be a counter starting at zero that goes up by one every time constraint (3.3) is not violated. The next Call off Point for position $N_{i,j}$ is then $N_{i,p}$. Note that the only difference between matrices M and N is that matrix M is filled with information about the moments when the truck arrives at the Deventer plant, while matrix N is filled with information about when the next Call off Point takes place.

In detail, the second approach solves the Integrated Supply Model as follows: Beginning at the start of the planning horizon, determine the next Call off Point by checking $N_{i,1}$. Let the corresponding value be k. For determining the next Call off Point of the same supplier, $N_{i,k}$ has to be checked and so on. This is done for all suppliers. In this approach, the Call off Points are now fixed and cannot be changed anymore. All that remains is to determine when the trucks can arrive at the Deventer plant. Note that in this approach not the complete matrix N has to be calculated, but only the entrances of the calculated sequence of Call off Points.

Ideally, the trucks all arrive exactly Δ_d later as the corresponding Call off Point. But, as with the first approach, it can occur that timeslots are blocked, due to reasons that are mentioned earlier. To solve this with the first approach, the truck had to arrive earlier such that the Call off Point had to be shifted backwards. As a consequence, the upcoming Call off Points had to be calculated again. By fixing the Call off Points and keeping the delivery times variable as in the second approach, if the ideal timeslot is blocked, the arrival of the truck can simply be shifted forwards until the first available timeslot is found. As a consequence, the Call off Points do not have to be calculated again. This leads to a sequence $c_1^i, \dots, c_{n_i}^i$ of Call off Points per supplier i, with n_i the number of Call off Points of supplier i. The next step is to determine the arrival times of the trucks UT_i, which fulfill the requirements of the minimal delivery time, the availability of the timeslot (thus, the timeslot must not be blocked) and that all the UT_i must be disjoint. Let us define $c_k^i + \Delta_d$ as release dates for scheduling the trucks, such that this becomes a simple single machine scheduling problem. By scheduling the arrival times of the trucks based on the earliest release date first, the arrival time of last scheduled truck gets minimized. The corresponding “Approach 2” model is implemented using Virtual Basic for Applications (VBA) in Excel. The algorithm for Approach 2 model is shown in Figure 3.3.

$$
\begin{array}{l}
For\ Supplier\ s = 1\ to\ LastSupplier\ S \\
\quad TimeSlot\ t = 1 \\
\quad CurrentOrder\ i = 1 \\
\quad While\ t < LastTimeSlot\ T\ do \\
\quad\quad p = t \\
\quad\quad While\ TF_t + Cap * \gamma > TF_{p+1}\ do \\
\quad\quad\quad Update\ p = p + 1 \\
\quad\quad End\ While \\
\quad\quad t = p \\
\quad\quad Update\ CoP_i := t \\
\quad\quad Update\ i = i + 1 \\
\quad End\ While \\
End\ for
\end{array}
$$

$$
Sort\ CoP_i\ ascending
$$

$$
\begin{array}{l}
TimeSlot\ t = 1 \\
For\ CurrentOrder\ i = 1\ to\ LastOrder\ L \\
\quad Update\ UT_i := CoP_i + \Delta_d \\
\quad k = 1 \\
\quad While\ \ UT_i\ is\ blocked\ do \\
\quad\quad Update\ UT_i := t + \Delta_d + k \\
\quad\quad Update\ k = k + 1 \\
\quad End\ While \\
\quad Block\ UT_i \\
End\ For
\end{array}
$$

Figure 3.3: Approach two model

First, the Call off Points are determined. Afterwards, the Call off Points are sorted such that the first order is the one of which the Call off Point is first. Finally, the arrival times of the trucks are scheduled following the “Earliest release date first” technique. Note that this model accounts for the blocked timeslots and that if the arrival time of a truck is scheduled that timeslot also becomes blocked.

This approach also has a consequence. If the ideal timeslot for the arrival of the truck of order i is blocked, the arrival time of that truck is shifted forwards in time. Because the corresponding Call off Point is fixed, the time between the start point of the Call off window, SP_i and the moment all materials are delivered to the corresponding section in production, EP_i, becomes longer. Remember from (2.9) that the replenishment time of order i is $EP_i - SP_i$. This means that the replenishment time becomes longer as a consequence of the second approach.

A longer replenishment time will result in more Kanban cards, as seen in (2.14), which leads to a higher inventory level. The only solution to this problem is making the replenishment time smaller, such that less Kanban cards are necessary, but this leads to smaller Call off windows and the occupancy of the trucks will be less. The tradeoff between a higher occupancy and a lower inventory is one that will have to be monitored and decided what is acceptable and what is not.

3.5. Discussion

In this subsection the potential and the limitations of both approaches are given. Based on this discussion, an adapted version of one of the approaches is presented in the next subsection.

The main difference between the two approaches is the length of the Call off windows. In the first approach, the Call off Points might get shifted backwards. As a result of which, the Call off windows are shortened, while with the second approach the Call off windows are always of maximum length. This means that the occupancy of the truck is higher using the second approach. Another benefit of Approach 2 is that the resulting scheduling problem is easier to solve than the scheduling problem of Approach 1, which had to be solved by optimization software.

The benefit of Approach 1 is that the maximum replenishment time is smaller or equal to the maximum replenishment time of the second approach. The reason for this is that with Approach 1the arrival times of the trucks can only be shifted backwards, which has a positive effect on the replenishment time. With Approach 2, if a truck cannot be scheduled at the preferred timeslot, the arrival time is shifted forwards in time, which has a negative effect on the replenishment time. A longer replenishment time means more Kanban cards, which means higher holding costs and more space needed to store the materials.

A limitation of both these approaches is that they cannot cope with the transition between the weeks. For both approaches a restriction has to be formulated, which stated when the last truck of the week has to arrive per supplier. This results in trucks that arrive on Friday afternoon with low occupancy. When a transition can be made between two consecutive weeks, the truck could arrive early Monday morning, while the order was sent to the supplier Friday afternoon of the previous week. This would mean that the possible “extra” truck at the end of the week due to the restriction that states the arrival time of the last truck per supplier, can be removed. As a result, the scheduled trucks would have a higher occupancy and obviously fewer trucks are needed to deliver all the required materials to the Deventer plant.

Another limitation is that the approaches both use timeslots of 45 minutes. The length of the timeslots is not only used for the arrival times of the trucks, but also for the determination of the Call off Points and for the determination of the predicted quantity of materials used in production. These predictions would be more accurate if they were based on shorter time intervals. Above that, if the length of the timeslots would be smaller, also the Call off Points could be placed closer to the time at which the truck is as full as possible.

The last limitation is due to practical reasons. With the current approach, the trucks arrive at the same time every day. The corresponding order is also send to the supplier at regular times. This means that it is easy to remember when the orders has to be send, which means that barely any mistakes are made by the workers of Bosch as well as by the workers of the suppliers. With the introduction of the ISM, trucks could arrive anytime and at irregular times. This means that the changes of making a mistake are increased.

After some discussion within Bosch, it has been chosen to modify Approach 2. This approach is modified to overcome some of the above mentioned disadvantages. The main reason to choose for Approach 2 is that it makes optimal use of the capacity of the trucks. Another reason is that the resulting approach has to be also implemented in the real world, as the scheduling problem, corresponding to Approach 2, is easier to solve than the scheduling problem corresponding to Approach 1. These advantages have outweighed the disadvantage of the longer replenishment times.

3.6. Extended Integrated Supply Model

In this subsection, the Extended Integrated Supply Model is presented. The EISM is an adapted version of the Approach 2 model described in Section 3.4. The changes made to the Approach 2 model are explained in the following.

One of the limitations of the Approach 2 model is that it could not cope well with the transition between consecutive weeks. This is solved by not only determining the arrival times of the trucks for the five days of the current week, but also for the first day of the next week. In this way, if a truck has a Call off Point that takes place at Friday afternoon, it may be planned to arrive at the Deventer plant the "next" morning, just as any other truck. All the arrival times of the trucks that arrive the next week are recorded and regarded as fixed input for the truck schedule of the next week.

The limitations that the length of timeslots must be 45 minutes and that the variations of the unloading patterns per supplier are irregular, are solved within one adaption in the following way. For each supplier, the maximum number of trucks per day during the whole year is estimated. This estimation of the maximum number of trucks for supplier s is denoted by NoT_s. For each supplier s, NoT_s timeslots are reserved for a possible arrival of a truck of supplier s. These reserved timeslots for supplier s are denoted by the set PT_s. The trucks can only arrive at one of the reserved timeslots of its supplier. Note that not all the reserved timeslots have to be used for the arrival of a truck. The reserved timeslots have to be chosen such that the time between two consecutive reserved timeslots of any supplier is at least 45 minutes. This is the time that is needed to unload the truck.

The choice of the reserved timeslots is based on tests with different compositions of timeslots. The aim is to choose the reserved timeslots in a way such that the maximum replenishment time is minimized. The test with a composition that all reserved timeslots are bundled together, had the longest maximum replenishment time. With this composition, the average time between the preferred truck arrival time and the first available reserved timeslot was the longest. Eventually, a composition is chosen where the reserved timeslots are spread out over the day, while still accounting for the opening hours of the suppliers. Note that all the reserved timeslots of the suppliers are disjoint.

It remains to specify how it is determined which reserved timeslots a supplier uses for its truck arrival and which not. To determine this, the scheduling of the trucks is slightly adapted compared with the Approach 2 model. First, the Call off Points of supplier s are determined as with the Approach 2 model and the truck is scheduled to arrive at least Δ_d later than the corresponding Call off Point. From that point in time, the first available timeslot from the set PT_s is chosen for the arrival of the truck. This can be calculated independently for each supplier based on the order of the corresponding Call off Points.

In the adapted model, the length of the timeslots on the production side has been chosen to be 15 minutes, which is the acceptable interval to determine the predicted quantity of materials. This reduced length on average leads to a higher occupancy of the trucks, as it may take 15 or 30 minutes longer until the capacity constraint (3.1) is violated.

The limitation that with the ISM the trucks arrive at irregular times is overcome by introducing the reserved timeslots. With the introduction of the reserved timeslots, the timeslots are dedicated to only one supplier, which decreases the chances of making a mistake with sending the orders and unloading the trucks.

The introduction of the reserved timeslots has also a disadvantage. The replenishment times may become longer. The number of available timeslots for the arrival of a truck of a specific supplier is reduced with the EISM, as a truck can only arrive at a reserved timeslot of its supplier, instead of any available timeslot. This means that the average time between the preferred arrival time, Δ_d after the Call off Point, and the actual arrival time is on average longer as with the Approach 2 model.

4. Implementation and results

In this section, the implementation and the results are presented. In the first subsection, the implementation of the ILP and the Approach 2 model are discussed. After that, the results are given for both approaches for the Integrated Supply Model. Then, these results are compared to the results of the Extended Integrated Supply Model in the next subsection. Finally, a description of the implementation of the EISM into the real world situation at the Deventer plant and the results achieved with this implementation are given.

4.1. Implementation

In this subsection, the implementation of both approaches is explained. The first approach is solved using an optimization software called AIMMS. The second approach is solved using Excel. In section 3, some insight is given of how the ILP and the Approach two model solve the Integrated Supply Model. The aim of this subsection is to give more insight into the input and output of both models.

The ILP model uses the first approach to solve the ISM. It uses the matrix M as input to determine when the trucks should arrive. Next to the matrix M, it needs information about which timeslots are blocked. For this, the opening hours from all the suppliers are taken as input. Furthermore, the arrival times of the trucks that deliver the small volume materials are passed to the algorithm. These materials are delivered by the transportation company Veenstra. The arrival times of these trucks are fixed during the whole year. Then, the working times of the different production lines are also incorporated into the ILP as input. The latter also accounts for the lunch breaks held. The quantity of materials that is specified per day in the production planning can be evenly spread over these working times. Moreover, the minimum delivery time is regarded as input. The transportation costs of €275 per arriving truck at the Deventer plant is taken as cost function. With this input, the ILP can determine which timeslots are blocked for the arrival of a truck of HSL.

The ILP model determines the arrival times of the trucks for the complete week. A problem arises for the materials that are used in production after the Call off Point of the last truck of the week per supplier. These materials must be delivered to the Deventer plant, but that cannot be done in the same week. To ensure that these quantities of materials are also ordered, for each supplier, the quantity of materials used in production after the last Call off Point of that supplier of the previous week are taken as input for the ILP.

Another limitation of the ILP is already discussed in 3.5. The ILP does not cope well with the transition between two consecutive weeks. As a consequence, a lower bound for the arrival time of last truck of the week per supplier is used. This ensures that the quantity of materials used in production after the last Call off Points is small enough such that the first truck of the next week does not have to arrive too early on Monday morning.

All the input is summarized in an Excel file. The AIMMS software reads this input data from the Excel file and then solves the ILP model as discussed in Section 3.3. After solving the ILP, AIMMS writes the output to the same Excel file. The output consists of a 0-1 matrix U. The position $U_{i,j}$ indicates whether a truck of supplier i arrives at the Deventer plant at timeslot j or not. The matrix U can be used to display an overview of the truck schedule for the whole week. Figure 4.1 shows (a part of) an example of this overview.

TimeSlot	Time	HSV	Intermeco	Lentink	Timmerije
48	06:00				
49	06:45		Veenstra		
50	07:30		Too Early		
51	08:15				
52	09:00				Timmerije
53	09:45		Veenstra		
54	10:30				
55	11:15		Lunch Break		
56	12:00		Veenstra		
57	12:45				
58	13:30			Lentink	
59	14:15		Intermeco		
60	15:00		Veenstra		
61	15:45	HSV			
62	16:30				
63	17:15				
64	18:00				
65	18:45				
66	19:30		Lunch Break		
67	20:15		Veenstra		
68	21:00				
69	21:45		Too Late		
70	22:30				
71	23:15				

Figure 4.1: Overview of the output of one day

The input of the Approach 2 model is similar to that of the ILP. Only where the ILP uses the matrix M to determine the arrival times of the truck, the Approach 2 model uses the matrix N to determine the Call off Points.

All the input data are put on an Excel file and the resulting Approach 2 model of the ISM is solved using this Excel file. This results again in the matrix U as output. But in this case, also a table with all the Call off Points and corresponding arrival times of the truck has to be specified. This is necessary, because with the Approach 2 model, the time between the Call off Point and the arrival time of the corresponding truck is not fixed, in contrast with the first approach. A consequence of this is that the workers have to use the table of Call off Points and arrival times of the trucks in order to send the order at the correct time to the corresponding supplier.

4.2. Results of the Integrated Supply Model

In this subsection, the results of the Integrated Supply Model are presented and discussed. The input for this test is based on historical data. The production planning and the working times from the weeks 13 until 17 of the year 2014 are used for the prediction of the quantity of materials used in production. The rest of the input is based on the same historical data.

As mentioned in the previous section, the current approach at Deventer plant predicts the number of trucks for the current week. The maximum number of trucks needed per supplier for one day of the current week is estimated. This amount of trucks is used every day of that week per supplier. This approach is easy to use, but the performance of this approach, measured in the number of trucks, is not very good.

Both developed approaches use the ISM to solve the supply problem of Bosch. The first approach uses a fixed delivery time and after the truck arrival times are calculated, the Call off Points can be determined. This approach is solved by the optimization software AIMMS. The second approach focusses more on a maximum length of the Call off windows by calculating the Call off Points first and then uses a variable delivery time to determine the arrival times of the trucks. This approach is solved with a heuristic in Microsoft Excel. Both approaches predict the quantity of materials used in production per 45 minutes.

For the comparison of the different approaches, the number of trucks and the average occupancy per week are considered. Note that there is a correlation between the number of trucks and the average occupancy per week. The test period has some singularities. Due to Easter, the Friday of week 16 and the Monday of week 17 are holidays and the Deventer plant was closed on those days. The achieved results are shown in Figure 4.2 until Figure 4.4.

Current

# Trucks	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	10	10	10	8	8
Intermeco	10	5	10	4	4
Lentink	10	10	10	8	8
Timmerije	5	5	5	4	4
Totaal	**35**	**30**	**35**	**24**	**24**

Occupancy	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	65%	60%	68%	74%	73%
Intermeco	51%	80%	47%	85%	80%
Lentink	52%	53%	65%	64%	67%
Timmerije	41%	39%	49%	44%	48%
Totaal	**52%**	**58%**	**57%**	**67%**	**67%**

Figure 4.2: Results of the current approach

Approach 1

# Trucks	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	7	7	7	6	6
Intermeco	6	4	5	4	4
Lentink	5	5	6	5	5
Timmerije	2	2	2	2	2
Total	**20**	**18**	**20**	**17**	**17**

Occupancy	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	84%	80%	83%	85%	82%
Intermeco	78%	94%	85%	76%	71%
Lentink	85%	90%	94%	83%	86%
Timmerije	85%	82%	90%	64%	68%
Average	**83%**	**87%**	**88%**	**77%**	**77%**

Figure 4.3: Results of approach 1

Approach 2

# Trucks	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	7	7	7	6	6
Intermeco	5	5	5	4	4
Lentink	6	6	6	6	6
Timmerije	3	3	3	2	2
Total	**21**	**21**	**21**	**18**	**18**

Occupancy	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	82%	80%	84%	84%	79%
Intermeco	90%	78%	85%	80%	69%
Lentink	74%	77%	88%	78%	73%
Timmerije	58%	54%	61%	71%	70%
Average	**76%**	**72%**	**80%**	**78%**	**73%**

Figure 4.4: Results of approach 2

The number of trucks in the current approach is between 30 and 35 per week (except for the week with less working days). The number of trucks with the other approaches is between 17 and 21. This is more than a 40 % saving. The inferior performance of the current approach is also noticeable in the average occupancy of the trucks. There are even individual trucks with occupancy of 30%. Both new approaches perform up to 60% better than the current approach.

When comparing the two developed approaches, a couple observations stand out from the rest. The first observation is that the first approach performs better. The main cause for this is the last truck of the week. The consequence of this is that the next week starts with a small amount of materials that has to be delivered from the previous week, but in the meantime the average occupancy goes down, because without the lower bound on the arrival time of the last trucks, the trucks would not be scheduled.

The first approach in combination with AIMMS makes that the arrival times of the trucks can be divided more evenly over the whole week. By fixing the Call off Points, Approach 2 is less flexible with the arrival times of the trucks. There is only one week where the second approach performs slightly better than the first approach. A possible explanation for this is that the amount of materials that is still needed to be delivered to the Deventer plant from the previous week was more beneficial for the second approach than for the first.

The achieved results of the approaches are also compared based on the transportation costs. These costs are related to the number of trucks and are given as €275 per truck. These results are shown in Figure 4.5 until Figure 4.7.

Costs	Week 13	Week 14	Week 15	Week 16	Week 17	**Total**	Savings
#Trucks	35	30	35	24	24	**148**	-
Costs	€ 9.625,00	€ 8.250,00	€ 9.625,00	€ 6.600,00	€ 6.600,00	**€ 40.700,00**	-

Figure 4.5: Costs of the current approach

Costs	Week 13	Week 14	Week 15	Week 16	Week 17	**Total**	Savings
#Trucks	20	18	20	17	17	**92**	56
Costs	€ 5.500,00	€ 4.950,00	€ 5.500,00	€ 4.675,00	€ 4.675,00	**€ 25.300,00**	€ 15.400,00

Figure 4.6: Costs of Approach 1

Costs	Week 13	Week 14	Week 15	Week 16	Week 17	**Total**	Savings
#Trucks	21	21	21	18	18	**99**	49
Costs	€ 5.775,00	€ 5.775,00	€ 5.775,00	€ 4.950,00	€ 4.950,00	**€ 27.225,00**	€ 13.475,00

Figure 4.7: Costs of Approach 2

As expected, both approaches have lower total transportation costs than the costs of the current approach. In five weeks both approaches save around 50 trucks, which means a saving of around €15,000. As Bosch produces fifty weeks per year, this leads to yearly savings of around €150,000. This is a 40% saving compared to the current approach.

As mentioned in the previous section, the Approach 2 model is chosen to be extended. Although the performance of the first approach is better measured in the total number of trucks, this difference comes mainly because of the last trucks of the week. In the Extended Integrated Supply Model the lower bound on the last truck of the week per supplier is removed, which should make the second approach perform better. The main reason for this is that the Approach 2 model makes use of longer Call off windows. The results of the resulting EISM are presented in the next subsection.

4.3. The results of the Extended Integrated Supply Model

In this subsection, the results from the Extended Integrated Supply Model are presented. These results are based on the same test period as for the Integrated Supply Model.

As mentioned in the previous section, the Extended Integrated Supply Model is an adapted version of the ISM. Next to some features that are added, the main improvement is that the lower bound on the arrival time of the last trucks of the week per supplier is removed. The results of the EISM are shown in Figure 4.8 and Figure 4.9. These results can be compared to the results shown in Figure 4.2 until Figure 4.7.

EISM					
# Trucks	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	5	6	5	5	5
Intermeco	4	4	3	3	4
Lentink	4	5	6	5	4
Timmerije	1	2	2	2	1
Totaal	**14**	**17**	**16**	**15**	**14**

Occupancy	Week 13	Week 14	Week 15	Week 16	Week 17
HSV	98%	98%	99%	98%	99%
Intermeco	99%	99%	99%	99%	99%
Lentink	99%	98%	98%	97%	99%
Timmerije	99%	100%	100%	100%	100%
Totaal	**99%**	**99%**	**99%**	**99%**	**99%**

Figure 4.8: Results of the EISM

Costs	Week 13	Week 14	Week 15	Week 16	Week 17	**Total**	Savings
#Trucks	14	17	16	15	14	**76**	72
Costs	€ 3.850,00	€ 4.675,00	€ 4.400,00	€ 4.125,00	€ 3.850,00	**€ 20.900,00**	€ 19.800,00

Figure 4.9: Costs of the EISM

The first observation that can be made is that the number of trucks needed in week 13 is significantly less than with the ISM. This reduction has two reasons: One is that the restriction is removed that the last truck of the week has to arrive at the Deventer plant Friday afternoon. The other reason is that in the EISM the prediction of the quantity of materials used in production is determined every 15 minutes instead of 45. As a consequence, the occupancy of the trucks is closer to the desired occupancy. This makes e.g. the difference in the number of trucks in week 13.

The second observation that can be made is that the occupancy is very close to 100%. The reason for this is that the five week period is seen as one big period and the orders are divided almost perfectly. The reason that not all trucks have occupancy of 100% is that due to the fact that the prediction of the quantity of materials is discretized and cannot be seen as a continuous process.

All of this leads to a saving of 72 trucks, which is almost half of the trucks needed with the current approach. This reduction of trucks can also be seen in the transportation costs. The reduction is approximately €20,000, which is about half of the costs with the current approach. Yearly, this comes down to approximately €200.000 savings.

4.4. Real world implementation

In this subsection, the real world implementation of the Extended Integrated Supply Model is discussed. First, the problems that arose with the implementation are discussed. After that, the solutions to these problems are presented.

The results achieved with the EISM based on the historical data gave the responsible persons at Bosch enough reasons to implement this method into their own supply chain. From week 40 of the year 2014 on, the EISM is running for the suppliers HSV and Timmerije. If all initial diseases are cured, the other two suppliers will be added. The presented results of the EISM implemented at Bosch are of weeks 40 until 44, in which the other two suppliers were not added yet.

During the implementation period, some adaptions were made to the Extended Integrated Supply Model, most of which resulted from problems that arose as a consequence of the implementation.

As mentioned earlier, the blocked timeslots are already built up of the opening hours of the suppliers, the timeslots when Veenstra trucks deliver materials and the working times of the workers in production at the Deventer plant. The Expended Integrated Supply Model (EISM) also accounts for days that the Deventer plant is closed due to holidays. Next to that, it accounts for timeslots that are not available due to planned meetings or other hours in which the Deventer plant is closed. By making these adaptions, the predicted quantity of materials used in production better fits the actual quantity of materials. Above that, the trucks cannot be planned to arrive during days that the Deventer plant is closed.

For the integration of all suppliers, several changes were made. First of all, some extra suppliers are added to the model. Although these suppliers do not use the dock nor do they have to be scheduled, these suppliers need to get their orders. With the implementation of the EISM, the orders of these added suppliers were not taken into account. The reason for this was that the workers fully relied on the output of the EISM, however the later added suppliers were first not shown on this output. Another option that is added to the existing model is that it now can be selected for which supplier(s) the model should determine a solution. In this way, suppliers can be left out when they are closed, or when a new solution is needed only for some suppliers.

With the ISM, the assumption was made that prediction of the quantity of materials used in production is equal to the actual quantity of materials. In practice, this is not the case. This is due to last minute changes in the production planning, standstills in production and due to an extra margin in the production planning. This margin is to foresee the event that the workers in production work faster than planned. In that case, there are enough materials to go further with producing heating boilers.

To cope with this difference between the actual quantity of materials and the prediction, the safety margin is introduced. This margin has as a consequence that during planning, a part of the truck is left empty such that (small) changes in the actual quantity of materials can still be delivered by the truck. If this would not have been done, there is a higher risk on a standstill in production. A disadvantage of the above is that the average occupancy differs by the safety margin from the full capacity of the trucks. Within the EISM, the safety margin is used as input.

The last change is made to avoid that multiple Call off Points could overlap. Because the Call off Points are fixed, the Call off Points of different suppliers could take place at the same time. This would mean that two different orders have to be sent at the same time to different suppliers. This could lead to confusions, which result in the wrong order being sent to the suppliers.

Furthermore, the time between the Call off Point and the truck arrival might get longer than the minimum delivery time, because the truck arrival might get shifted forwards in time. This also could lead to confusions at the supplier, because the next order could be send to the supplier before a truck delivered the previous order. As a consequence, the wrong order could be loaded at the supplier and delivered at the Deventer plant.

To avoid these possible confusions, the Call off Points and the moments that the order is actually sent to the supplier are decoupled. The Call off window is still the window in which the materials are gathered that go on the order, but now there also is an order window in which the order has to be sent to the supplier. In this way, the moments when the orders have to be sent to the supplier can be regulated, such that no orders have to be sent at the same time. Note that it is important that the order is sent within the order window. If the order is sent too early, there is a chance that the Call off window is not ended yet and on the other hand if the order is sent too late, there is a chance that the supplier has too little time to process the order.

To give the workers an overview of the Call off windows, order windows and trucks arrival times, a monitor is put up next to the computer where the orders has to be sent to the suppliers. This monitor is shown in Figure 4.10. On this screen an overview is shown of the upcoming order windows. In the left area the supplier is shown with the truck arrival, date and time. The first line displays the amount of time left before the next order window opens. Furthermore, the Call off window for the next order is shown. In the right part, the start time of the next three order windows are shown with the appropriate supplier.

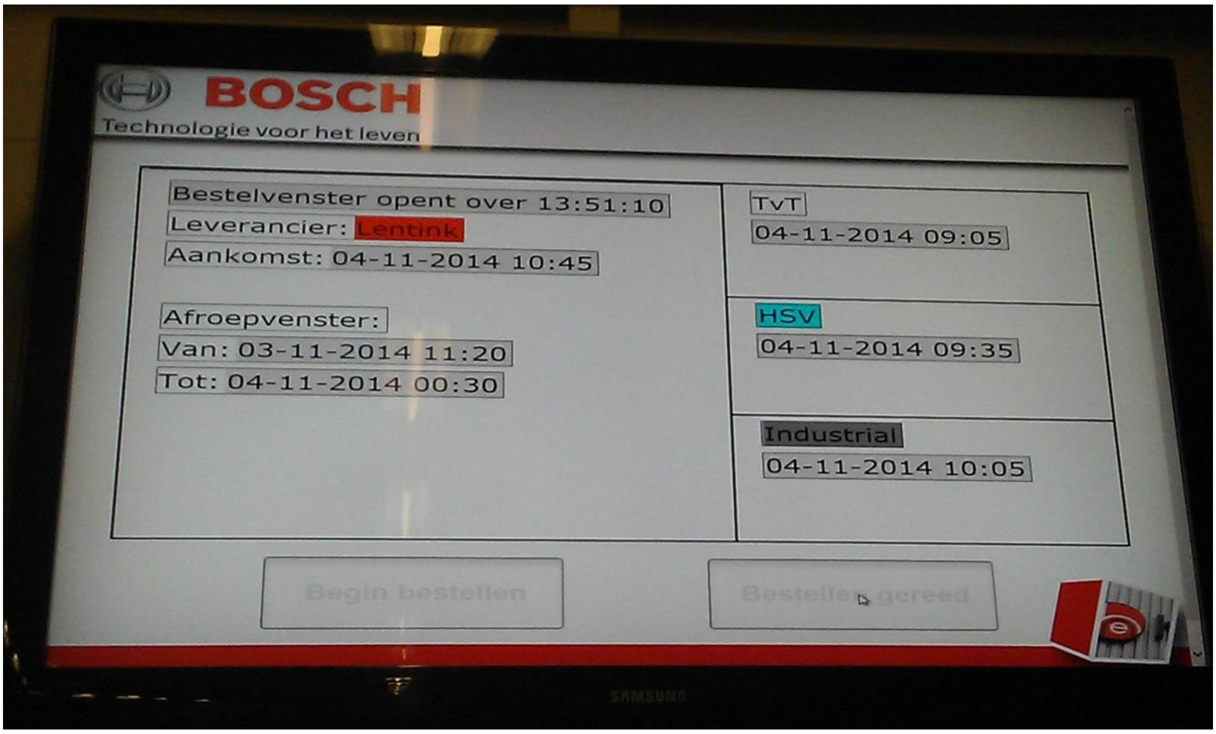

Figure 4.10: Monitor

To help the workers remember that an order has to be sent within the order window, the screen flashes orange when the order window starts and it flashes red when the order window has ended. At that time, a loud sound is made to alert the workers that an order has to be sent immediately. The worker can indicate that the order is sent by clicking the two buttons at the bottom of the screen.

This system is developed with help of an external IT-company. It uses the output of the Extended Integrated Supply Model to display the information at the monitor.

All the input data that is needed for applying the EISM is shown in Figure 4.11 and Figure 4.12 . The screens, given in these figures, pop up when the macro for a new solution of EISM is activated.

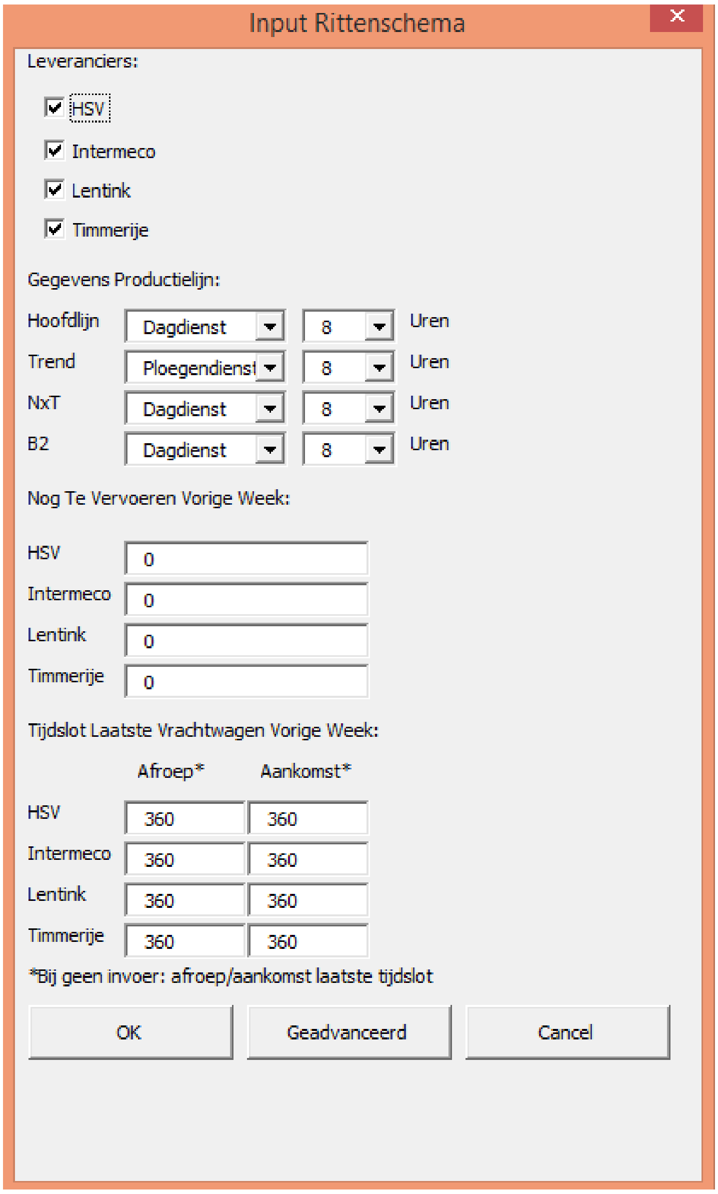

Figure 4.11: Basic Input Data

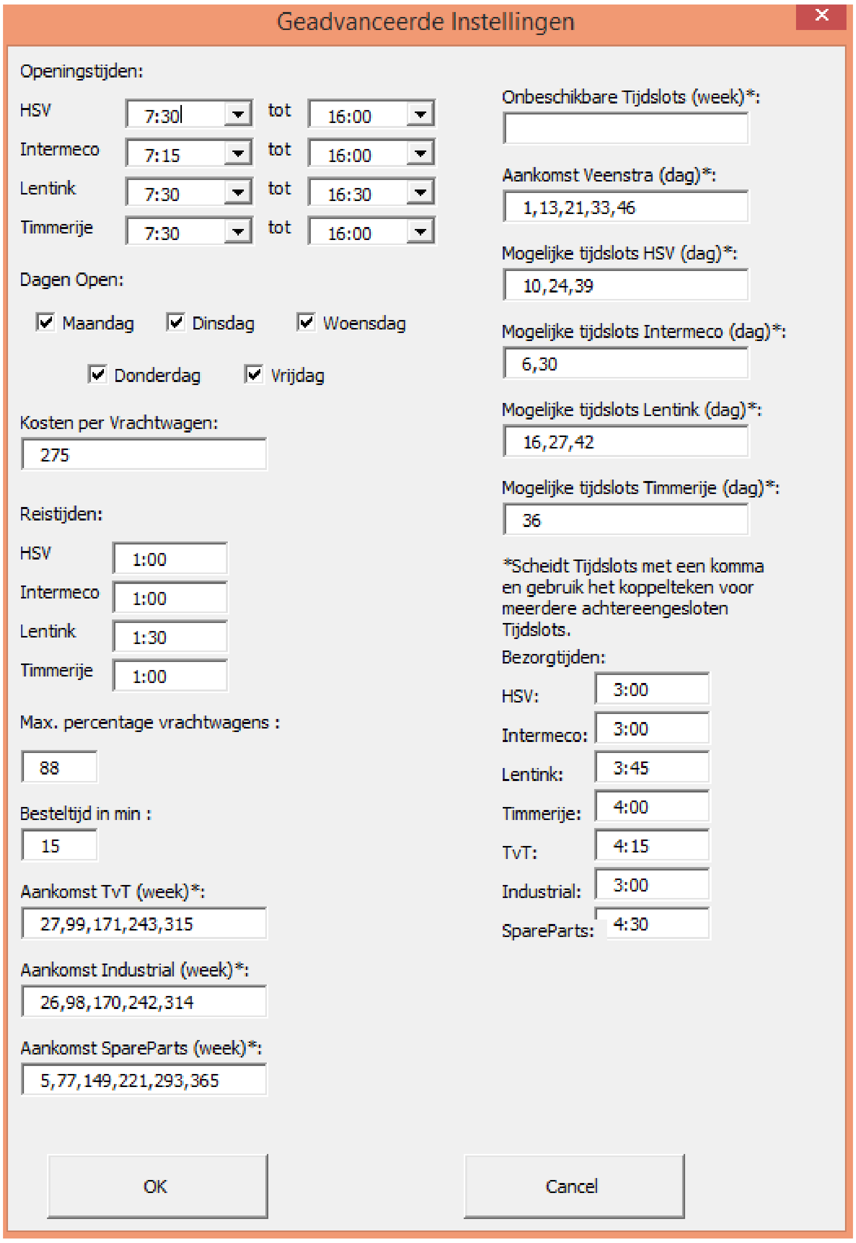

Figure 4.12: Advanced Input Data

4.5. *Results of the real world implementation*

In this subsection, the results of the Extended Integrated Supply Model implemented in the real world situation are presented. First, some Key Performance Indicators (KPI) are stated, most of which coincides with the KPI's which have been used for the tests based on historical data. After that, the results of this real world implementation are given.

In the previous subsection, the implementation of the EISM into the supply chain of Bosch is described. One of the mentioned aspects was the use of the safety margin. For the test with the historical data, the safety margin was not needed, because it was assumed that the predicted quantities of materials used in production were equal to the actual quantities of the materials.

The use of the safety margin makes that more trucks are needed to deliver the materials to the Deventer plant. As a consequence, the performance of the EISM implemented into the real world situation should be worse than the performance of the EISM based on the historical data.

To measure the performance of the EISM in the real world implementation, Key Performance Indicators (KPI) are used, most of which coincides with the KPI's of the figures 4.2 until 4.9. There are 5 KPI's: Occupancy trucks Timmerije, occupancy trucks HSV, Difference prediction versus actual quantity of materials used in production for both Timmerije and HSV and the number of trucks that have occupancy of more than 100%. For each KPI, a target is defined. The occupancy of the trucks of both suppliers should be 84%, because the safety margin $\gamma = 0.16$. For the difference between the predicted and the actual quantity of materials, a margin of 10% is allowed. For the number of trucks that have occupancy of more than 100%, the target is set to zero, because a truck with an occupancy of more than 100% could lead to a standstill. Note that the KPI's only consider the results of two suppliers as only those suppliers were integrated into the real world implementation.

The results shown below are the daily results over a period of 5 weeks, namely week 40 until week 44. The first Key Performance Indicator is the occupancy of the trucks of Timmerije. This KPI is shown in Figure 4.13. A linear trend line is drawn through the points.

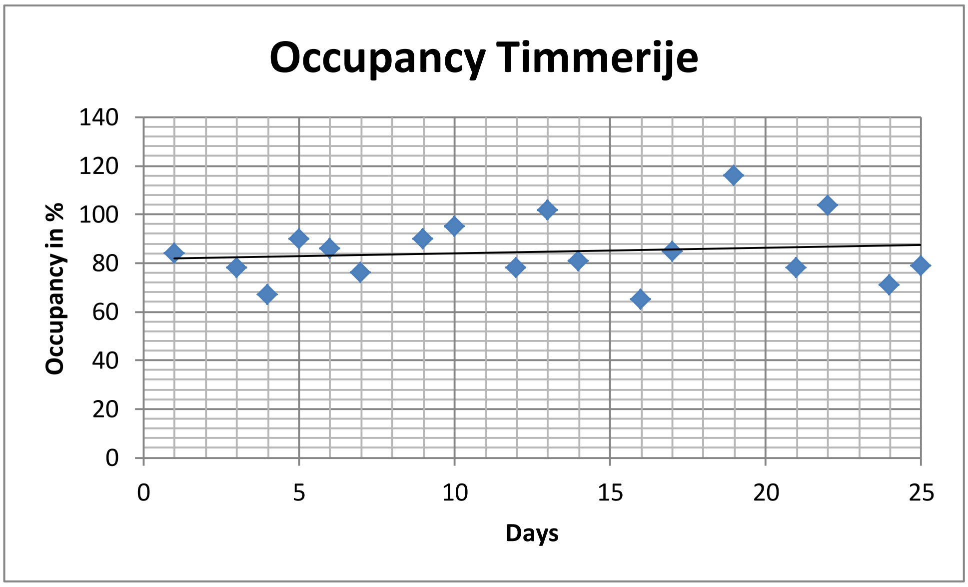

Figure 4.13: Occupancy of the truck of Timmerije

A few observations can be made. The first observation is that at some days the trucks have an (average) occupancy of more than 100%. The reasons for this are discussed when treating the KPI of the number of trucks that have occupancy more than 100%. The second observation is that there are fewer points than the number of days. The reason for this is that not every day a truck of Timmerije had to arrive at the Deventer plant. Another observation is that the scattering of points is big. The reason for this is that the actual quantity of materials used in production differs from the predicted quantity of materials. Above that, it sometimes happens that Kanban cards are forgotten at the production area, or they are not scanned, which causes irregularities. The last observation is that the trend line has a positive tendency, which tends to the safety margin, which was set to 16%, i.e. $1 - \gamma = 0.84$.

The next KPI is the occupancy of the trucks of HSV. The results are shown in Figure 4.14. The first observation that can be made is that the scattering of the points is less than with the results of Timmerije. The reason for this is that Timmerije produces materials that have a greater volume than the materials of HSV. This means that if there is a small difference in the number of heating boilers produced, the difference in the occupancy of the trucks of Timmerije will be much greater than the difference in the occupancy of the trucks of HSV. Above that, the quantity of materials supplied by HSV is 3 times more than the quantity of materials supplied by Timmerije. This makes the average occupancy of the trucks of HSV per day less sensible for small changes. Another observation that can be made is the outlier of day 15. The reason of the low occupancy of that day is a standstill in production earlier that week. The linear trend line drawn through the points shows a positive trend. This means that during the implementation period, the occupancy gets higher. This is a consequence of adapting the Extended Integrated Supply Model as mentioned in the previous subsection.

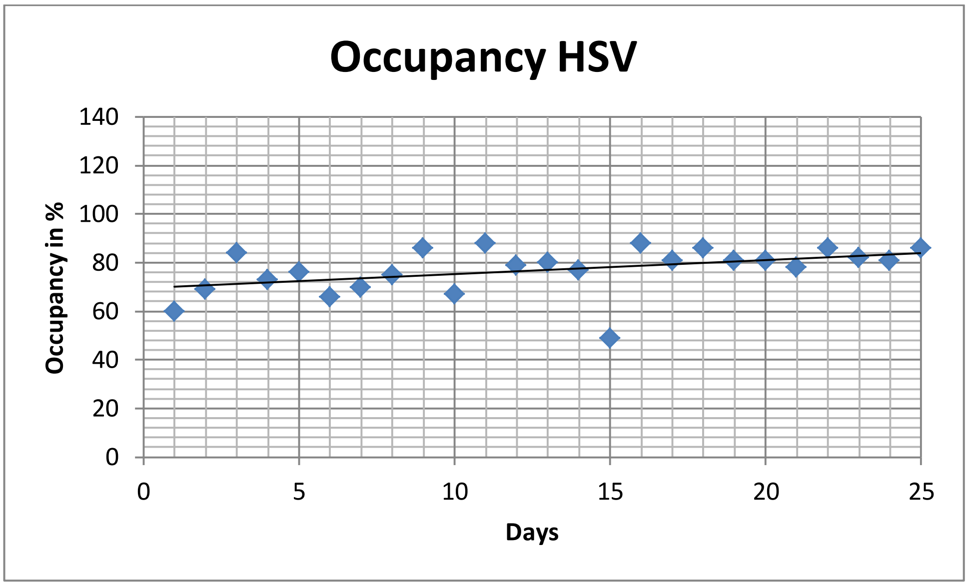

Figure 4.14: Occupancy of the trucks of HSV

The next KPI is the difference between the predicted quantity of materials used in production and the actual quantity of materials used in production of the materials supplied by Timmerije. The results of this KPI are shown in Figure 4.15.

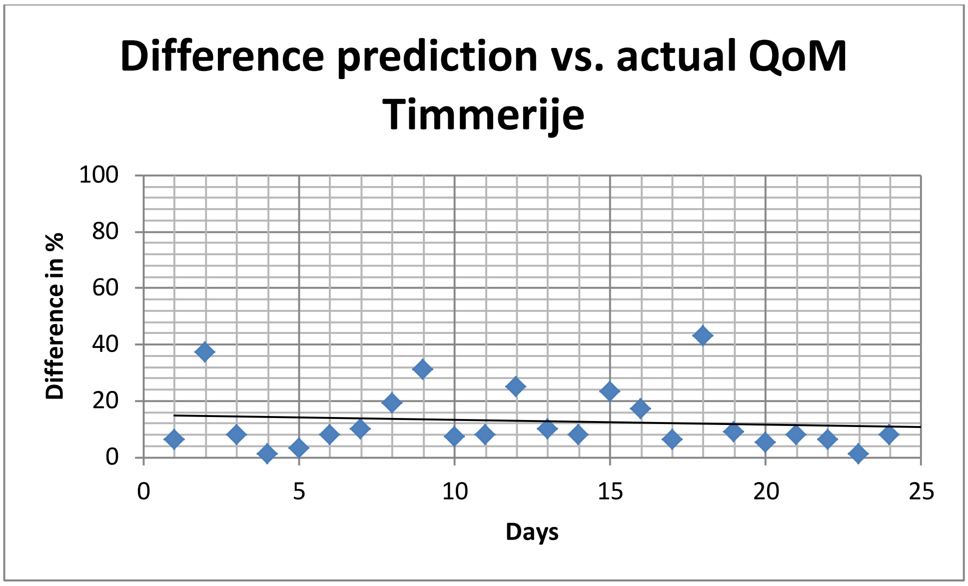

Figure 4.15: Difference prediction vs. actual Quantity of materials Timmerije

The observations that can be made are that there are some days where the difference is greater than the allowed margin of 10%. This can be due to many reasons, the exact of which is not known. The differences shown in this figure can also be seen in Figure 4.13, for example the spike of day 18 in this figure results in an occupancy of the truck of the next day of 120%. The trend line through the points in Figure 4.15 shows a negative trend and tends to the allowed margin of 10%.

The next KPI is the difference of the predicted quantity of materials used in production compared to the actual quantity of materials of the materials supplied by HSV. The results are shown in Figure 4.16.

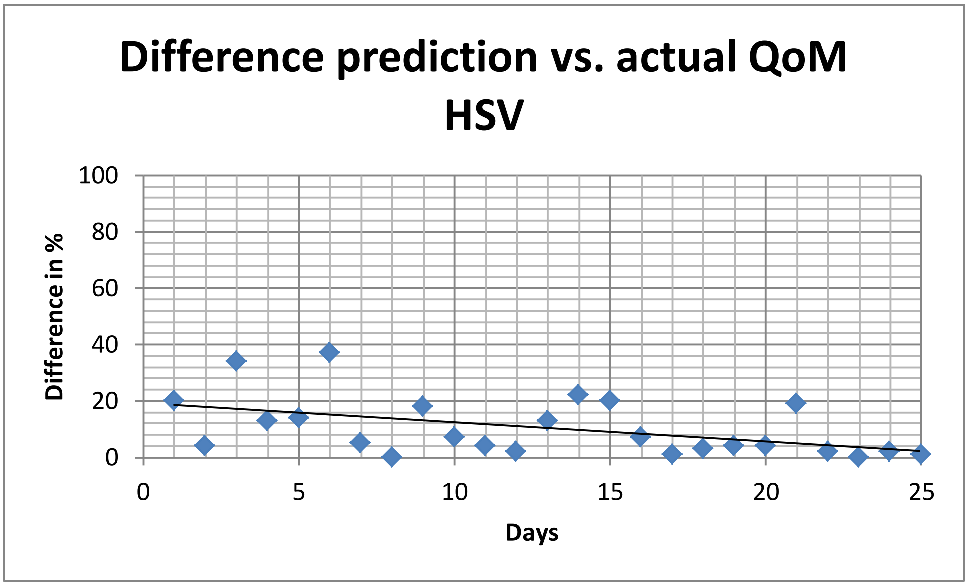

Figure 4.16:Difference prediction vs. actual Quantity of materials HSV

As with Figure 4.15, there are days where the difference between the predicted and the actual quantity of materials is much higher than the allowed margin of 10%. By adapting the prediction of the quantity of materials the last ten days, the difference becomes acceptable. The difference shown in this figure also translates to the occupancy of the trucks of HSV. For example the spikes of days 13, 14 and 15 in this figure translates to very low occupancy in the trucks of HSV at day 15. The trend line has a strong negative tendency, which tends to a difference between the prediction and the actual quantity of materials that is almost zero.

The last KPI is the number of trucks with occupancy of more than 100%. The results are shown in Figure 4.17.

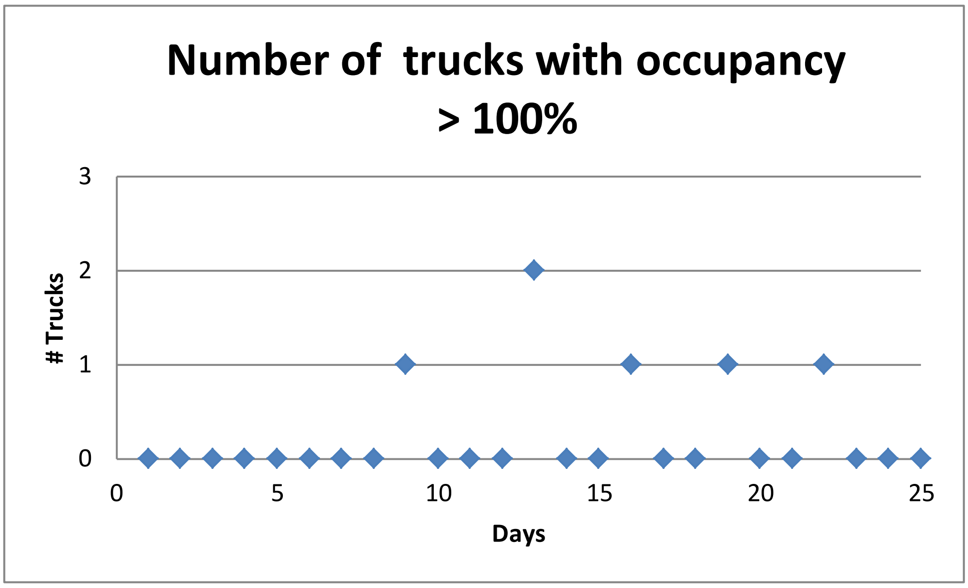

Figure 4.17: Number of trucks with occupancy >100%

The results of this KPI should be zero all the time. A total of 6 trucks had occupancy of more than 100%, most of which had occupancy of 103% or less. In these cases the materials still fitted into the truck, probably because there was some freedom in the floor place index data of some materials. As a consequence, some materials needed less space in the trucks than stated in the data. The days, at which these high occupancies occurred, the difference between the predicted and actual quantity of materials also is high. The reasons that some trucks have occupancy of more than 100% can be the following: A standstill in production may have the consequence that during the next period more heating boilers were made to achieve the target amount of heating boilers. Another reason can be that some Kanban cards were scanned too late, with the consequence that these Kanban cards are scanned at the next Call off window such that the next truck has to deliver too many materials. Next to that, the predicted quantity of materials used in production can differ compared to the actual quantity of material due to other reasons. The consequence is that materials are used at a different time and in a different quantity.

The consequence of a truck that has occupancy of more than 100% is that the supplier calls Bosch to inform them that not all the materials fit into the truck. The worker of Bosch has to decide instantly which materials are left at the supplier and are delivered the next time.

All the Key Performance Indicators show good results, although the occupancy is lower than the results in theory. This means that the number of trucks in the real world application may be higher than the optimum number of trucks which follows from a calculation afterwards based on the real data. This can be improved by choosing a lower safety margin such that the Call off windows are longer and the trucks more full. However, this cannot be done at Bosch at this moment, because the difference between the predicted and actual quantity of materials is still too big. This can be improved by optimizing the Kanban process or choosing another production control method. Other production control methods are discussed in the next section. In this section, it remains to show the final cost saving of the implementation of the Extended Integrated Supply Model. The transportation costs of the EISM are compared to the transportation costs of the current approach. The results are shown in Figure 4.18.

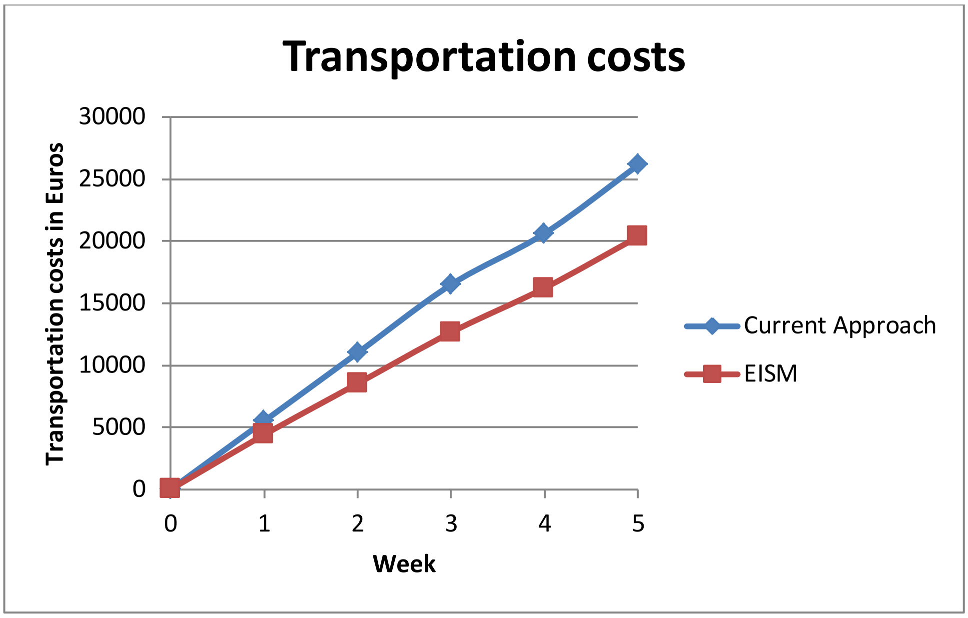

Figure 4.18: Transportation costs of the EISM and the Current approach

The total transportation costs of the current approach and the EISM are respectively €26,125 and €20,350, a difference of almost €6,000. Note that the EISM is only implemented for two of the four suppliers. If all the suppliers were implemented, the cost saving would have been around €12,000 for these 5 weeks. This comes down to a total cost saving of €120,000 for the whole year. This is less than the €200,000 predicted based on the results of week 13 until 17. As mentioned earlier, the main difference comes from the fact that the predicted quantity of materials used in production is not equal to the actual quantity of materials. As a consequence, the occupancy of the trucks must be lowered to cope with possible differences between the predicted and actual quantity of materials. A note has to be made that the weeks 40 until 44 are weeks of the high season, where the production is at maximum capacity. In the low season, the difference in transportation costs between the current approach and the EISM will be greater. It is reasonable to account for a yearly saving of €150,000.

5. Comparison of different production control methods

In this section different production control methods are compared to the Kanban system. The Extended Integrated Supply Model performed excellent in theory, but when the predicted quantities of materials were compared to the actual quantities of materials used in production, some improvement can be made. In the implementation in week 40 until week 44, the safety margin was set to a quite large value of 16%. However, this safety margin was necessary to cope with the differences between the predicted and actual quantity of materials.

The aim of the comparison between the Kanban system and other production control methods is to see if there can be any improvements made such that the safety margin can go down to 10% or 5%. The production control methods that are compared to the Kanban system are CONWIP, a hybrid method between CONWIP and Kanban and the Heijunka method.

First, the disadvantages of the Kanban system are discussed. After that, the other production control methods are explained. Note that the Kanban system was already explained in section 1.3. Finally, a comparison is made between the different production control methods and a conclusion is drawn if there is another production control method that may suit better to the situation of Bosch.

In section 2.4 the restriction was explained that the production must not come to a standstill. That meant that the inventory at the timeslot that the inventory is restocked must be high enough to cope with the quantity of materials used in production. Remember that at EP_i, all the materials of order i are delivered to the corresponding section at production. For each order, this is the only moment the inventory is restocked. The corresponding restriction (2.7) is $I_j(EP_i) \geq Q_j([EP_i\ , EP_{i+1}])$.

The problem with the Kanban system is that it works with the materials that have already been used instead of the materials that are going to be used. This could lead to problems, as explained in section 2.4. Another problem of the Kanban system is that it works with Kanban cards. These cards must be collected and scanned such that the ERP system can record the quantity of materials that are being used in production. The time that it takes to do this results in a delay between the time a material is used in production and the time that the ERP system records that the material is used. This delay causes also a difference between the predicted and actual quantity of materials used in production. In order to reduce the safety margin, this difference should be decreased. One way to do this can be by using another production control method than the Kanban system.

The first production control method is CONWIP, which stands for CONstant Work In Process. This is described among others by Spearman et al in [SWH90]. CONWIP is a pull system that is similar to the Kanban system. It is applicable to a wider range of production environments than the Kanban system. CONWIP also works with cards that are used to authorize work, but where the Kanban system uses cards for each individual part, CONWIP uses cards for the entire production line. It works by triggering production from a backlog of system cards and once the product is at the end of the production line, the system card goes back to the queue to wait to be triggered again. This queue is the backlog. Production is triggered when production is needed. Figure 5.1 shows a schematic representation of the CONWIP system.

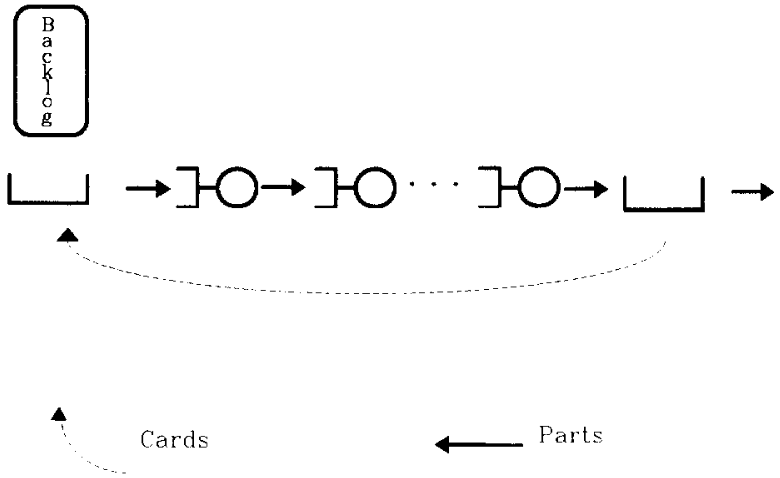

Figure 5.1: A schematic representation of CONWIP; Fig.2 in [SWH90]

CONWIP has as advantage that the Work In Process can be monitored better. As a consequence, the Work In Process is lower than with the Kanban system. A benefit of a lower WIP is among others that the chance to detect quality issues early, is larger. Because there are viewer products in the system, if a defective part is added to the product, this is detected without many defective parts already in production. Above that, the inventory levels of individual parts are reduced by the explicit control over the whole production line instead of the individual parts. By reducing the Work In Process, the inventory levels are also reduced.

Although CONWIP reduces the inventory levels, the problems of the Kanban system described above are also present for the CONWIP. First, the order is still based on materials used in the past, instead of the production in the future. With CONWIP, materials can be ordered if the whole product is produced. This means that it takes longer before that is recorded that individual parts are used in production. As a consequence, the replenishment time becomes longer, which may counter the benefit of lower inventory levels because longer replenishment times causes higher inventory levels.

The delay between the time that a material is used in production and the moment that it is recorded by the ERP system becomes longer with CONWIP, but it can cope better with a (strong) changing demand. By using the backlog queue, the Work In Process can be controlled better. However, if the change in demand is too large, the inventory levels will be still depleted.

A hybrid method is described by S. Sharma & N. Argawal in [SA09]. This method comes from the fact that CONWIP may have a high level of WIP inventory towards the upstream end if there is any failure of intermediate machines or bottlenecks. The Kanban system is designed to prevent an individual buffer from attaining the desired limit. The hybrid method is CONWIP supplemented with the Kanban concept such that the entry of components in the system can be prevented after a certain limit. This is achieved by local WIP control mechanism using Kanban and global inventory control using CONWIP.

In [SA09], the hybrid method is tested and compared to the Kanban system and CONWIP. These three production control methods were tested with four different distributions of demand. In case I, the binomial distributed demand was used. In cases II to IV, respectively the exponential, lognormal and Poisson distributed demand was used.

Different performance indicators were used to compare the three production control methods, among others the average Work in Process, the average throughput and the average total costs.

The manufacturing system used for the simulation is shown in Figure 5.2. In this figure, RM stands for the inflow of raw materials, WS stands for the work stations, of which there are four. Finally, FP stands for the outflow of finished goods. Each workstation is made up of a machine and an output buffer. The circles and triangles represent the machines and output buffers respectively, in each manufacturing process.

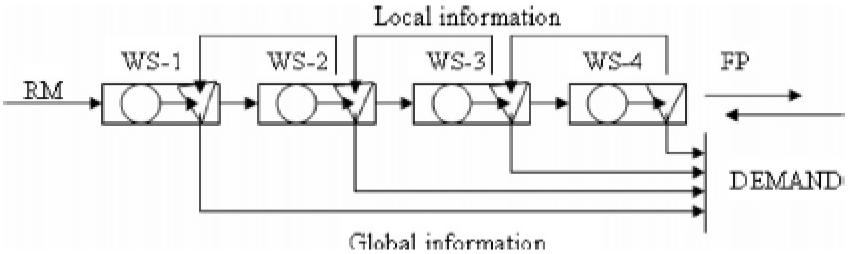

Figure 5.2: A four stage manufacturing system; Fig.1 in [SA09]

The result of this comparison was that Kanban performed overall better than CONWIP and the hybrid production control method. The global ranking for the Kanban system performed more than 60% better than the CONWIP and more than twice as good as the hybrid method in case I. In the cases II and IV, the Kanban system also performed better, although the difference was only around 20% in comparison with the CONWIP. In case III, CONWIP outperformed the Kanban system. It performed 20% better than the Kanban system. The hybrid method is in all cases the worst performing production control method of the three tested.

These results do not suggest that the CONWIP or the hybrid production control method should replace the Kanban system in order to improve the results of the Extended Integrated Supply Model. Although the CONWIP outperformed the Kanban system in the lognormal distributed demand case, the disadvantages of CONWIP mentioned earlier still remain.

In [PAS09] D. Powell et al. described the Heijunka method as follows: “Heijunka is the method used in lean to level production in terms of both product volumes and product mix. Level production is a way of scheduling daily production for different types of products in a sequence to even out peaks…”. They also described a new production control method called Every Product Every (EPE). This control method schedules to produce every product each cycle. The EPE method is a promising concept for process-type industries. In process-type industries, large investments are made in large machines, often at the cost of substantial changeover times. At Bosch, there are no changeover times between the different machines at the production lines. Above that, not that many different types of heating boilers are made at the Deventer plant. That is why the EPE method does not seem to be a good alternative to the existing Kanban system at Bosch.

The Heijunka method does have some potential for the implementation at the Deventer plant. As mentioned at the beginning of this section and is shown in Figure 2.5, the problem of the Kanban system is that the ordered materials are based on the quantity of materials used in production in the past. However, the inventory levels must be high enough such that a standstill in the future is prevented. A problem arises when the demand changes strongly. The Heijunka method ensures that the peaks in the demand are evened out. As a consequence, the quantity of materials ordered with the Kanban system comes closer to the use of materials in the following period. This would mean that less inventory is needed.

For the Extended Integrated Supply Model, the implementation of the Heijunka method would mean that the prediction of the quantity of materials used in production would better fit the actual quantity of materials. The prediction uses the production planning to predict the quantity of materials used in production per timeslot. As mentioned in section 3.2, this is done by spreading the quantity of materials evenly over the timeslots that the production runs. When the Heijunka method is implemented, the actual quantity of materials used in production is also more evenly spread out over the day. This means that the predicted quantity of materials would fit better the actual quantity of materials. As a consequence, the safety margin could go down, which eventually leads to higher occupancies of the trucks and thereby to a lower number of trucks.

6. Conclusion and discussion

In this section a summary is given of this thesis and the conclusions are drawn. Furthermore, the problem statement is reviewed and a discussion is held to answer to what degree this thesis contributes to the problem stated in the problem statement. Finally, some recommendations on future work are given.

At the beginning of this thesis the problem was stated. The problem statement was as follows:

How must the Deventer plant be supplied with great volume materials such that the total costs are minimized?

The problem statement consisted of three sub-questions:

When must the great volume materials be ordered?

When must the trucks arrive?

Which amount of great volume materials must be ordered?

The answer to these questions is different for each instant and depends on the given input. Section 2 gives an insight in the restrictions concerning these questions. Sections 2.1 and 2.2 are devoted to the first sub-question. The second sub-question is answered with help of the restrictions discussed in section 2.3 and in section 2.4 the third sub-question is treated.

To answer the question of the problem statement, the Integrated Supply Model (ISM) was developed. The ISM describes the restrictions that are present in answering this question. In this model three decision variables are present: The Call off Points, which are the moments that the orders are send to the suppliers, the arrival times of the trucks at the Deventer plant and the number of Kanban cards, which determines the inventory levels of the materials.

To solve the ISM, two approaches were developed. The first approach focusses on the arrival of the trucks. The Call off Points are determined based on the truck arrivals, which are chosen as close to the ideal moments as possible. The second approach focuses on the Call off Points. Based on those chosen Call off Points, the corresponding truck arrival times are determined.

The approach which has shown to have the most potential was the second approach. The main argument for this conclusion was that the trucks were on average more filled than for the first approach. This meant that fewer trucks were needed to deliver the materials to the Deventer plant. Both approaches had some limitations, the most important of which was the transition between two consecutive weeks. To overcome this problem, extra trucks had to be deployed. Because the second approach had the most potential, this approach was improved and adapted to the Extended Integrated Supply Model (EISM). This model solved the limitations both approaches had.

The approach currently used at Bosch, the two basic approaches of the ISM and the EISM were compared based on historical data. The main criteria for the comparison was the number of used trucks per week. The EISM outperformed the other methods and reduced the number of trucks by almost 50% compared to the current approach. This leads to a yearly saving of around €200.000 on transportation costs.

Due to these results, the EISM was implemented into the real world situation at the Deventer plant. This model was integrated into the supply chain of Bosch, whereby it took into account half of the suppliers. The other suppliers follow when the model runs to the satisfaction of Bosch. During the implementation several adaptions had to be made. The implementation of the EISM in this real world situation led to a yearly saving of around €150.000 on transportation costs if all suppliers are implemented.

Conclusion

It is recommended that Bosch uses the Extended Integrated Supply Model, because of the financial and time savings. The number of trucks is reduced significantly, which saves on the transportation costs. Due to the reduced number of trucks, the workers have to unload fewer trucks, although the trucks that arrive at the Deventer plant are more filled. Despite this, the unloading time is reduced. Furthermore, the time for making the truck schedule is reduced by implementing the EISM using Virtual Basic for Applications of Excel. The responsible person only has to give the correct input and the EISM calculates the new truck schedule. This can be done in under a minute.

Although the EISM is chosen to be implemented into the supply chain of Bosch, this model has some disadvantages. The most important is that the replenishment time becomes longer than with the other approaches. The replenishment time measures the time between the moment a material is used in production and the moment that it is delivered to the Deventer plant. As a consequence of a longer replenishment time, the inventory level of the materials is higher. This means that more space is needed to store the materials and higher holding costs.

From tests with the historical data and from the real world implementation it follows that the use of the EISM does not lead to significant longer replenishment times. The maximum replenishment time becomes at most two hours longer, which does not lead to significant higher inventory levels.

In section 5, a comparison is made between the Kanban system and other production control methods. The Heijunka method has a potential to lead to a better performance of the EISM. This must be researched further before this can be implemented into the production of Bosch. Furthermore, other options to reduce the gap between the predicted quantity of materials used in production and the actual quantity of materials have to be found and reviewed.

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