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Aggregate bottleneck capacity planning in the automotive industry

Bakens, S.

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Aggregate Bottleneck Capacity Planning in the Automotive Industry

by
Stan Bakens

Student identity number: 0832820

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TU/e supervisors:

Dr. Y. Ghiami,	*TU/e, OPAC*
Dr. Ir. H.P.G. van Ooijen,	*TU/e, OPAC*

Company supervisors:

Paul Hiel,	*Inalfa Roof Systems, Operations*
Dirk Sneijkers,	*Inalfa Roof Systems, Logistics*

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This one is dedicated to the one who has shown me how to ride a rocky road

Abstract

In the dynamic and competitive environment of the automotive industry, first-tier suppliers struggle to decrease costs, while improving delivery lead times and reliability and flexibility. In this research we present two aggregate production capacity planning models that optimize scheduling related production costs, for flow line assembly systems in the automotive sector; (1) the bottleneck capacity planning model (BCPM), and a simplified (2) IRS model. The BCPM is a mixed-integer non-linear programming model that addresses production workforce capacity per working station in the production system, by means of a worker contribution function. Furthermore, the distinction between permanent and contingent workers is made in the modeling. A relaxation of the BCPM is presented, which linearizes the problem by replacing worker contribution functions with discretized capacity scenarios. The IRS model is incorporated in a planning tool that is used for (sensitivity) analyses in a case study, at a first-tier automotive supplier. Results show that the master production scheduling can be improved, such that system costs decrease by approximately 9.6%. Besides the optimization of the production schedule, by means of the planning model, the planning model itself can be improved by adaptation of input parameters.

Management Summary

This research focuses on the master production schedule (MPS) of the XC60-Kuga-Mondeo assembly line of the IRS-Venray plant. The relation between customer forecasts, relevant production costs, and costs parameters related to production planning, are examined. The goal of this research is to investigate the problems that are reported regarding the discrepancies between the customer forecasts and the production schedule, causing over-time work, idle time of workers, and emergency shipment costs. The research provides a modeling approach that considers all relevant costs factors, while optimizing the production planning problem, and automates the execution of the planning. The emphasis of this research is on the production process and finished goods; the supply side, of the internal processes, is out of the scope of this research.

Problem Description

IRS updates its aggregate production plan, the MPS, once every week for each assembly line. The planning horizon of the MPS is 15 weeks, including the week at the time of re-scheduling. The MPS is based on demand forecasts that are provided by the customer, the current inventory levels, and the available capacity, as is common for master production scheduling (Hopp & Spearman, 2000). The available capacity, of the IRS assembly line, is adjustable in terms of number of shifts that are worked per week and the output per time unit can be adjusted. The production line contains multiple working stations of which the output can be adjusted by altering the number of operators that are allocated to that station, as is shown in Figure i. The different combinations of number of workers, allocated to the production line, and outputs are known as capacity scenarios. The possibility to adjust the number of shifts that are worked per week is out of the scope of this research, since it is considered a long-term management decision.

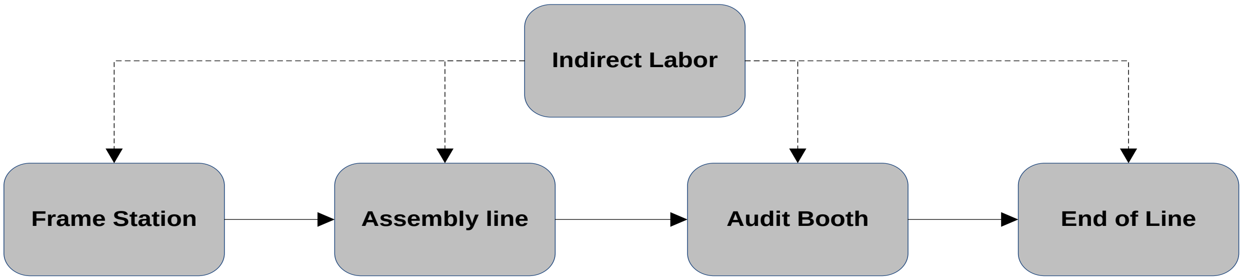

Figure i: Assembly line configuration at IRS

Furthermore, four main product variants are produced on the XC60-Kuga-Mondeo assembly line. The demand forecasts that are seen, for each product, fluctuate during the planning horizon, causing uncertainty that need to be coped with. Due to very high penalty costs, when causing a production stop at the customer, backorders are not allowed and are prevented at all endeavor. Hence, customer orders must be fulfilled. The workforce consists of a fixed pool of permanent employees and a pool of contingent workers that can be easily hired, from an external labor supply agency, or dismissed. New employees must be trained before becoming productive and being able to work autonomously. These characteristics resulted in the following research assignment:

Develop a production control methodology for a single, multi-product flow line production system with discrete dynamically adjustable production capacity per working station, constrained by limited production capacity, high backordering costs, and a demand fulfillment requirement.

Research Approach

The research is conducted in three phases; the analysis phase, the method development phase, and the case study phase. In the analysis phase the characteristics of the current production process and the planning process are examined. Also, the demand is analyzed and the current performance is assessed. These measures serve as inputs for the modeling in the method development phase and serve as baseline measure in the case study phase.

The developed models in the second phase are designed to be applicable to production environments similar to the IRS production environment, including IRS's other assembly lines. Two models are developed; the bottleneck capacity planning model (BCPM) and a simplified IRS model. The first is a mixed-integer non-linear programming model, which optimizes production planning for a multi-product flow line with multiple production stations. This model explicitly allocates operators to a particular station in order to calculate the best production schedule given demand and constraints. The constraints in this model include a minimum and maximum number of workers per station. The model is allowed to hire or dismiss contingent workers and optimizes over labor- (wages and costs for hiring or dismissing contingent workers) and inventory costs. Furthermore, backorders are included in the modeling and a training period for new workers is included, in which the new operators are not productive. This model implicitly schedules an efficient allocation of workers over the production system and consequently exposes efficient capacity scenarios. The simplified IRS model, on the other hand, is based on the assumptions of the BCPM. This model uses capacity scenarios to calculate an optimal production plan, which are retrieved from the idea that each production station has its own output-per-worker contribution function. This function describes the behavior of a specific working station when adding a worker to that station. The possibility to schedule backorders is eliminated in the IRS model. The use of capacity scenarios enables the model to become linear, and thus more computationally efficient.

In the case study phase the simplified IRS model is used to test whether the developed planning method improves the production planning performance of IRS. A testing period of 10 re-scheduling efforts over an 11-week period is used to compare the baseline measure with the case study results, retrieved from the simulations with the IRS planning model. Furthermore, a sensitivity analysis is performed to assess the influence of the used parameters in the planning model and to increase the performance of the model.

Results

The results from the three research phases have shown that the demand IRS faces is very volatile. However, the change in average demand is almost negligible and changes in demand volume are more often delayed or expedited demand, than an absolute increase or decrease in demand over the long-term. The MPS of IRS shows to be less volatile (more stable), but the final planned production quantities fluctuate between weeks; indicating that the production schedule is not flat. Furthermore, demand shows to be normally distributed.

When evaluating the baseline measure, it is shown that 8.80% of the total system costs are caused by emergency shipments and over-time working. This implies that emergency measures were taken to prevent orders to become overdue. This might indicate that safety stock levels could be reconsidered. Hence, two alternative approaches are proposed to calculate safety stock levels; approach 1 includes the incorporation of demand volume uncertainty in the calculation of the safety stock, while approach 2 extends that approach with the inclusion of demand lead time uncertainty. Both approaches are based on the characteristics (mean and standard deviation) of the demand that is actually faced by IRS. Therefore, safety stock levels are better fit to the production environment of IRS and broadly applicable.

Furthermore, cost parameters were estimated, which are the inputs of a planning methodology. These parameters are given in Table i. The estimated costs that are provided here help to understand the quantitative importance of the balance between workers and inventory.

Table i: Costs parameters of IRS (December 2015)

Parameter	Salary permanent worker (per hour)	Salary contingent worker (per hour)	Cost of Hiring a contingent worker	Cost of dismissing a contingent worker	Annual holding cost (%/€/Year)
Costs	€30.10	€34.02	€3,402	€500	26.77%

When comparing the performance of the developed production planning tool and the actual performance of IRS, a cost reduction up to **9.6%** can be achieved by implementing the methodology that is proposed in this thesis. The planning model that is set according to the parameters, as presented in Table i, can be improved by adjusting the model such that the computational algorithm is used more efficiently. The main results of the research are presented in Table ii.

Table ii: Planning model performance results

Model	Inventory costs	Labor costs	Acquisition costs	Utilization	Total costs	Performance increase
IRS performance	€ 26,926	€ 754,656	€ 35,118	95.16%	**€ 816,700**	0.0%
True IRS model	€ 43,808	€ 738,326	€ 3,000	95.14%	**€ 785,134**	3.9%
Optimal model	€ 21,836	€ 703,024	€ 13,206	92.88%	**€ 738,066**	9.6%

Conclusion and Recommendations

The production planning of IRS can be improved in two areas; first, the production plan can be improved by adopting the planning tool that is developed in this research. This could result in a cost saving of €371,724 annually, while fulfilling demand, and complying with all production requirements, set by IRS management. On the other hand, the production planning process could be automated by implementing the planning tool and scheduler's time is saved. To fully benefit from the proposed model the following main recommendations could be followed:

- Train schedulers and other stakeholders of the production planning tool, such that they are able to understand and work with the production planning (tool).
- Roll-out the planning tool to all production lines in a factory to fully benefit of its potential. This would save time for the production planning department, since all MPS planning would be automated. Also, production schedule quality is likely to be improved.
- Examine the re-planning frequency and planning horizon to improve the performance of the planning tool. The planning tool estimates an optimal schedule for the planning horizon, but is not able to incorporate re-scheduling efforts in its calculation.
- Update the parameters and inputs that are used by the planning tool on a regular basis. Elsewise, the tool might not provide reliable results (production schedules).
- Re-estimate the ratio between permanent and contingent workers for each production line to optimize labor costs. The IRS model could be used to calculate this ratio.
- Extend the planning model (by future research), such that is able to: optimize the production plan on factory level (multi-line), select the number of shifts that are worked per week, include the short-term order scheduling (hierarchical production planning), etc.
- Integrate production planning in the Enterprise Resource Planning system.

Preface

It has been a hell of a ride. Writing these words means that I am finishing my OML master thesis and accordingly finishing my time as student (at Eindhoven University of Technology). Graduating and obtaining my degree is the result of years of laughs, struggles, effort, and above all; a lot of good memories, of all the schools and universities that survived me. Now, the time has come to start preparing for a working life, and probably to grow up a bit.

I have enjoyed my time as student and especially the time during my master's track Operations, Management and Logistics. During this study I have been accompanied with good friends and fellow students who have challenged me to get the best out of myself. I have often surprised myself, when I felt I was with my back against the wall. Sometimes projects or exam weeks seemed impossible to pass, but I have learned that there is always a solution to complete a challenge successfully.

My master thesis research project was the greatest challenge of them all, but therefore the most educative. I learned a lot the past months; especially from the people who were closely watching me and my project. First of all, I want to thank Inalfa and my company supervisors Paul Hiel and Dirk Sneijkers for the opportunity they provided me. You have challenged and supported me during my research project and have also shown me what it is like to work as a professional in a commercial organization in a dynamic industrial environment. Furthermore, I would like to thank all co-workers of the CFT Topslider, who have seen me do nothing throughout my research project. I really know the most efficient way to get coffee now. Besides these colleagues I have had a lot of help of many people within IRS, which really made the difference. Thanks, to all who have spent little and great effort for my research, because it was always valuable to me.

Furthermore, I would like to thank Dr. Yousef Ghiami for his supervision during this research project. You have challenged me a lot, making me go lunatic at times. However, it always made me rethink my approach, ever resulting in an improved version of the thesis I am presenting here. I especially enjoyed your eye for detail and you have learned me a lot. Also my second supervisor, Dr. Henny van Ooijen, contributed greatly this thesis. Thank you for always asking the right, challenging questions, which put me often in the right direction.

There have been a lot of people who have supported me throughout this project (and the last 25 years of my life). I want to thank my parents, Ben en Nelly, for always believing in me and supporting me whenever I needed it. You have always enabled me to pursue my dreams and explore my talents. Furthermore, I need to thank my brother and sister who are always there, for their support and advice. Also, my friends deserve an acknowledgement. Without you guys, studying would not have been this successful or fun. My special thanks go to Rogé who has been my partner in crime during OML and who has found the time to give valuable feedback on my work. Lastly, I want to thank my girlfriend, Aniek, simply for being awesome.

Thank you,

Stan Bakens,
Eindhoven,
Januari, 2016

Contents

1 Company Description

In the automotive industry the power enjoyed by big car manufactures plays an important role in the whole supply chain settings and agreements. Using their power, these original equipment manufacturers (OEM) pressure their suppliers for lower prices, more flexibility in deliveries, higher reliability, and shorter lead times (Mansouri, Gallear, & Askariazad, 2012). The pressure OEMs put on their suppliers results in demand volatility at their suppliers, and thus throughout the whole supply chain (Chiang, 2011). In order to stay in business, suppliers in the automotive supply chain should comply with the conditions set by the OEMs. Elsewise, the consequences could be high penalty costs or loss of market share to competitors. The main drivers of this trend of pressure and supply chain nervousness are the globalization of the industry and the increasing competitiveness in the industry, in the past decades (Sturgeon, Memedovic, Van Biesebroeck, & Gereffi, 2009; Thun & Hoenig, 2012). The increasing competitiveness is mainly due to the financial crisis, started in 2007, and the battle for lowest priced cars in each segment (Ernst & Young, 2013).

These changes in the automotive industry resulted in very volatile demand volumes at the first tier suppliers in the industry, causing great difficulties in production and capacity planning for the suppliers. Last-minute increases or decreases in demand are common challenges in the automotive industry and are faced throughout the supply chain (García-Sabater, Maheut, & García-Sabater, 2012; Heneric, Licht, & Sofka, 2006). Volatility in demand causes nervousness in production schedules, and thus difficulties in workforce-, inventory-, and capacity planning. Inalfa Roof Systems Group B.V. (IRS) is one of those first-tier suppliers in the automotive industry. IRS develops and produces vehicle roof systems for all major car manufacturers worldwide and like other businesses in the sector; it is affected by the volatile demand as well. In this study we investigate and optimize IRS's production planning, with a focus on the master production schedule (MPS).

Since every company has its own characteristics, as well as each industry, an understanding of these characteristics is favorable to solve the problems that an organization faces. At IRS, customer demand forecasts show fluctuations throughout the planning horizon. Hence, a disparity between the customer demand and the production schedule is observed. This unbalance between demand and scheduling causes difficulties in workforce and materials planning, which results in unnecessary costs. To resolve and improve the problems that are faced, first an understanding of the problem (environment) has to be gained. Therefore, an overview of IRS and the production planning problem is given, in section 1.1. An outline of the organization is given with its most important departments, related to production planning. Then, a concise overview of the production process and the production planning process are given, closing with a brief overview of related departments and processes and a description of the company culture. Afterwards in section 1.2, an overview of trends in the automotive industry are given to delineate the competition that IRS Faces. Lastly, an overview of the structure of this thesis is given in section 1.3.

1.1 Inalfa Roof Systems Group

To get an understanding of the production planning problem, first an overview on the organization is given to grasp the challenges that are faced in this particular setting. IRS is a first-tier supplier of the automotive industry. The challenges that are faced by first-tier suppliers are similar. However, each organization produces unique products, and thus has its own characteristics as well, which varies from each specific organization to another. Therefore, the upcoming sections give a description of IRS and its production planning related processes, while these are elaborated regarding the production planning problem in chapter 2.

1.1.1 Organizational Information

Inalfa Roof Systems Group B.V. is a manufacturer of vehicle roof systems for the global car and truck industry. Roof systems, produced by IRS, include the following types; insliders, topsliders, exterior sliders, fixed panels, sunblinds and truck hatches (Inalfa Roof Systems, 2013). IRS is the second producer of vehicle roof systems, with a market share of approximately 20% worldwide (Broens, 2013). IRS was founded in 1946 and started its business in ironmongery. In the 50s and 60s IRS was specialized in gas and oil heaters and became one of the leading companies in the field. After that, production changed towards metal sheet forming in the seventies. In 1974 IRS started its current business, the production of vehicle roof systems, for Jaguar and Rover, which magnified over the past decades until it became IRS's core business. Nowadays, vehicle roof systems are the only product group that IRS produces; so all other production activities were abolished. IRS is producing roof systems for all top car manufacturers and all European truck manufacturers. The headquarter of IRS is located in Venray (the Netherlands) and production sites are located throughout the world (see Appendix A). IRS employs approximately 3500 people, and is rapidly growing.

IRS is mainly divided into three geographically dispersed departments; North America, Europe, and Asia. This research is conducted for IRS Venray, which is one of the three factories that are included in the European department, as is shown in Figure 1. The research is executed for the logistics and the operations department. For a visual overview of the organizational structure of IRS Appendix A could be consulted.

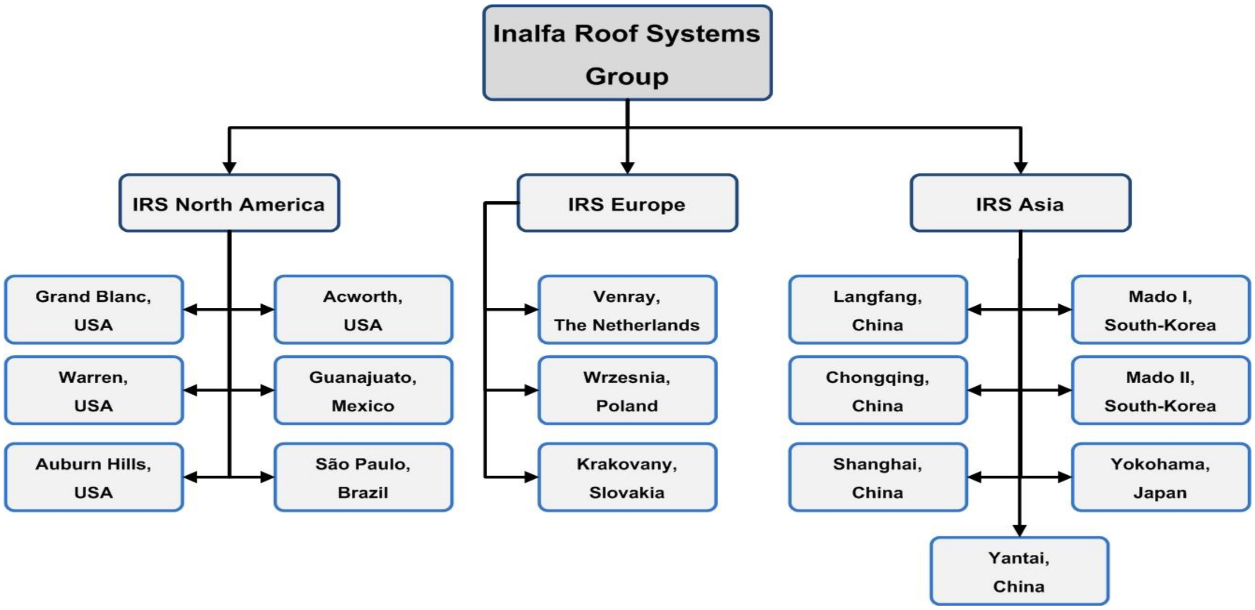

Figure 1: Organizational chart of Inalfa Roof Systems Group

1.1.2 Production Process

The labor intensive production process at IRS is executed on assembly lines. An assembly line contains multiple stations that need to be occupied by at least one person to be operational. Production lines are dedicated to specific products, although several products might be assembled on the same production line. When multiple products are produced on a production line, changeover times are involved when switching production from one product to another. The production of a roof system is mainly done by assembling purchased sub-components, however some components are produced "in-house" by IRS, instead of purchased from a supplier. For example, each assembly line has its own glass bonding station, where brackets are glued to the glass panel, such that the glass can be attached to the frame that is mounted in the car. Also, an end-assembly activity is executed on the electro-motors before assembly in the roof-system. Furthermore, rollo's (sliding sunscreens) are produced in the plant in Poland, for all newer products produced by IRS, while plans are being made to start in-house glass encapsulation processes (for all new products). These processes, although they can be considered as pre-assembly process, have to be taken into account when scheduling production.

The physical production process, in the Venray plant (see Figure 2), consists of a glass bonding (pre-assembly) step and the assembly of the end product. In between these steps a dry-time of the glue, varying between 4 to 48 hours depending on the used glue, is required, depending on the type of glue used. Furthermore, the electro motors used in production are assembled separately from the main assembly. Inventory is held for components for the glass bonding and for the motor assembly and components for the assembly process (WIP buffer), as well as for finished goods. The assembly is done by partly permanent employees, complemented with contingent employees hired from an external labor supply agency (ELSA).

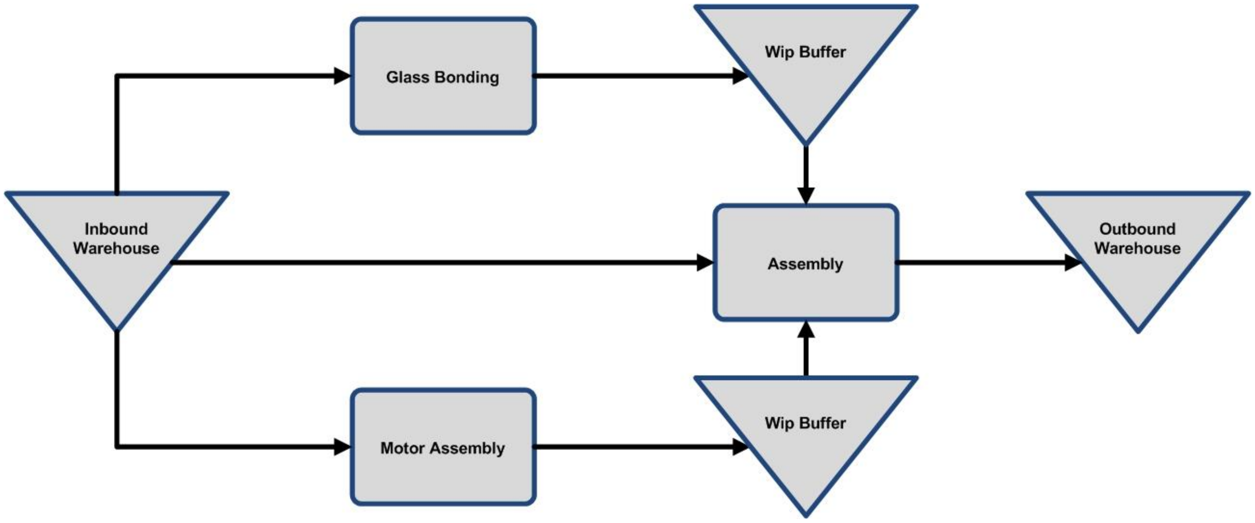

Figure 2: High-level representation of the IRS Venray production process

1.1.3 Production Planning Process

The production planning process is performed on a weekly basis, where the master production schedule (MPS) and a detailed daily planning are made, as is shown in Figure 3. The MPS is a schedule with a 15-week rolling planning horizon. The detail-level of the MPS is aggregated to whole weeks, which implies that the weekly demand is merged into one value. The detailed planning has a four-week planning horizon. Production is planned for each shift or hour specifically. Last-minute changes are made in this planning whenever problems occur. The planning activity itself involves many manual steps. The demand and production data is retrieved from the enterprise resource planning (ERP) system, after which the MPS has to be manually updated and afterwards uploaded to the ERP system. The planning is made manually, without the use of standardized methods or heuristics. The sole indicator for the planner to evaluate his planning performance is the inventory level, which colors white in the MS Excel-file (that is used to make the planning, see Appendix B), when the inventory level is within the desired bandwidth for that week. This is the safety stock (SS), which is derived from safety lead time. Furthermore, customer orders are received by means of long-term forecasts, short-term orders, and sometimes informal demand information is retrieved, for example through informal contacts of account managers with customers.

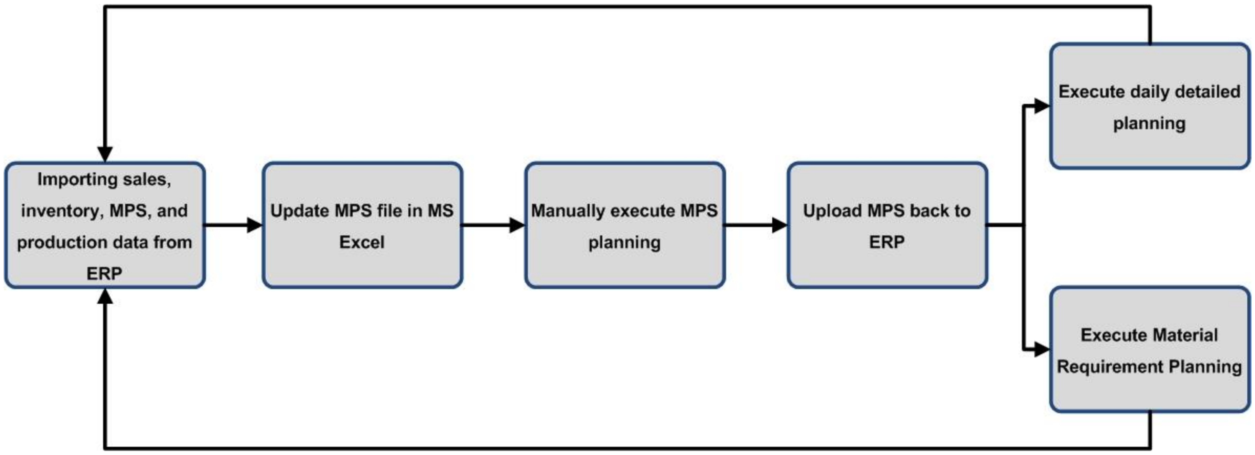

Figure 3: Production planning process of IRS Venray

1.1.4 Related Departments and Processes

Next to the production process and the production planning process itself, several other departments and processes influence the production scheduling. First, the sales department is responsible for the contractual agreements that are made with customers and adjustments on those agreements. These contracts include maximum demand volumes and deviations, and put obligations on both sides. Furthermore, the purchase department influences production (planning) when changing components of the roof systems in order to reduce costs. Using different parts in production might cause a change in the production process, or result in quality related problems. For example, changing from supplier of a component to reduce costs might result in quality problems when the new supplier is not capable of delivering good quality products. Also, supplier contracts are made by the purchase department, which specify the delivery requirements, such as lead time and quality. Additionally, the materials planning influences the production planning, because when components are out-of-stock unexpected changes in production order have to be made. Moreover, the ICT department has an influence on production planning through the support they deliver via enterprise resource planning (ERP) systems. Currently, the ERP system does not automate, monitor, or support production planning.

1.1.5 Company Culture

In the automotive industry *lean manufacturing* is the most common management paradigm to strive for continuous improvements and cost reductions, which originated at Toyota (e.g. the Toyota Production System (TPS)) (Herron & Hicks, 2008; Jabbour, De Sousa Jabbour, Govindan, Teixeira, & De Sousa Freitas, 2013; Liker, 1997; Nordin, Deros, & Wahab, 2010; Taj, 2008). This “lean thinking” spread across the automotive supply chain, and thus most suppliers of automotive parts adopted the lean manufacturing philosophy as well (Holweg & Pil, 2001). IRS is no exception on this industry’s standard.

Lean manufacturing philosophy offers a tool for analysis, through value stream mapping, and improvement of production systems, by means of reducing “waste”; all forms of unnecessary costs. The seven classic forms of waste in the lean thinking principle are; transport, inventory, motion, waiting, overproduction, over-processing, and defects (Rother & Shook, 1999). To be able to improve a production system according to the lean manufacturing philosophy some assumptions have to be addressed. Lean manufacturing assumes short (production) lead times, which means that items can be produced in a shorter time span than the delivery due date requires. Elsewise, true lean production is not possible, because no proper make-to order (MTO) production is possible, and safety stocks become necessary again. Moreover, lean manufacturing assumes production processes without line failures or quality rejects, and thus production planning should not consider these in capacity calculation.

Consequently, when these assumptions are not real, lean manufacturing might cause problems instead of resolving them (Lang Wood, 2012; Nayab, 2011; Shpak, 2015). However, all these features of lean thinking sound very promising, in practice it results in many problems. Lean management emphasizes the reduction of all "wastes", which might cause a company to reduce every form of costs, such as inventory, however this might sometimes be necessary. In those cases organization becoming too lean and thus costs arise that are due to system nervousness, for example.

1.2 Trends in Automotive Industry

When the TPS emerged at Toyota and has been proven successful, the automotive industry gradually adopted this manufacturing philosophy. Together with the adoption of lean manufacturing, the production systems at the industry's OEMs shifted from make-to-stock (MTS) to make-to-order production systems. This shift was driven by a change in customer demand; customers requested for more tailored solutions for their vehicle composition, instead of picking a vehicle out of a limited pre-specified selection (Holweg, Davies, & Podpolny, 2009; Holweg & Pil, 2001). Furthermore, the automotive industry is characterized by globalization, increasing competitiveness, uncertainty, and great power of the car manufactures (Chiang, 2011; Sturgeon et al., 2009; Thun & Hoenig, 2012; Volling, Matzke, Grunewald, & Spengler, 2013).

The problems that IRS faces are similar to the problems faced by other first-tier suppliers in the automotive sector. The change from MTS production to MTO production resulted in a change of production based on sales forecasts to production based on customer orders, at the car manufacturers (Sturgeon, Van Biesebroeck, & Gereffi, 2008). This trend was driven by the need for better production lead times, improved reliability on due date delivery, and better flexibility in production (Mansouri et al., 2012). The change to MTO production resulted in higher demand volatility at the suppliers, since OEMs reduced inventory buffers and thus their ability to cope with uncertainty. Other challenges are caused by an emerging globalization of the automotive industry (Ernst & Young, 2013; IBM, 2009).Globalization of industry is normally considered a driver of supply chain collaboration (IBM, 2009; Sturgeon et al., 2009; Thun & Hoenig, 2012). However, collaboration sounds more promising than it in reality is, since it results in demonstration of power instead of sharing of information and knowledge, in the automotive sector (IBM, 2009). In practice collaboration efforts are too little, which mainly causes customer pressure towards suppliers instead of benefits for both sides (Ernst & Young, 2013). Additionally, the research and development of components, in a car, is more often outsourced to the suppliers of the OEMs. Consequently, suppliers have long-term delivery agreements for the components, which make them the unique supplier of that component. Consequently, this has made them directly responsible for the quality of the products. For that reason, suppliers are forced to bare warranty claim risks, instead of the car manufacturers (Pavlínek, 2012).

All these risks are present and need to be coped with to be allowed to produce components for a car manufacturer. When a supplier chooses that it cannot live up to the expectations of the car manufacturer, it is most likely that this choice ends their cooperation. On the other hand, car manufacturers imply that the supply chain risk has grown in recent years and therefore risks have increased, and risk management practices have arisen at OEMs (Schwarz, 2008). These practices put more stress on the suppliers of the OEMs and thus complicating the supplier's position in the supply chain.

1.3 Thesis Outline

In this thesis we aim to address a production planning and scheduling problem common in the automotive industry. The contribution of this research is threefold. First, an analysis of the current performance of the production (planning) system at IRS is performed, which serves as baseline measure.

Second, a general model is built to optimize the production planning problems faced in automotive industry and a production control methodology is constructed to cope with the volatile demand. Lastly, the performance of the optimization model and production control method is tested on the IRS case, and compared to the baseline measure. The remainder of this thesis is organized as follows: a description of the production planning problem is given and a literature review about aggregate capacity- and production planning is presented in chapter 2. Also, attention is paid to solution methods for scheduling problems and gaps in literature are explored, which result in the research assignment and methodology. In chapter 3 a description of the IRS production system and the planning process is given, next to an analysis of the demand faced by IRS and the current performance of the production system. Afterwards, two models are developed that are designed to cope with the aggregate capacity planning problem, in chapter 4. In chapter 5 a case study is presented based on the IRS production system; a sensitivity analysis is executed, which reveals the influence of planning parameters on the behavior of the developed production planning tool. Thereafter, a brief implementation plan is given in chapter 6. Lastly, the conclusion of the research is given in chapter 7, in which research questions are answered, limitations of the research or discussed and recommendations are made.

2 Problem Description and Research Assignment

Now that we know the characteristics of the company, a further evaluation of the problem can be given. Especially, the MPS is considered in this research, which is a type of aggregate production planning at IRS (Hopp & Spearman, 2000). The MPS is the main driver of the material requirements planning (MRP), the workforce scheduling, inventory planning, production costs, and due date delivery performance (Junior & Filho, 2012). The master production scheduling is executed in an MTO environment in the automotive industry, which is a very competitive and volatile industry, as mentioned in chapter 1. To understand the problem, an awareness of the context of the problem is required, which is given in section 2.1. Thereafter in section 2.2, an outline of the production planning problem is given, which is the driver of this research, by means of a problem statement. These problems are the input of the literature review in section 2.3. This section is closed by the research assignment and methodology, in section 2.4.

2.1 Problem Context

When considering the context of a problem, several aspects emerge. Some characteristics of the problem are related to the industry and thus common for many companies within the supply chain, while others are specific for an organization. The characteristics of the production system raise constraints, but also possibilities, whereas other forces cause difficulties; to be able to model a fitting solution for a given problem, the characteristics of the problem have to be respected. In addition, the nature of these characteristics might imply that some facets are given and other aspects can be changed, against possible costs or investments.

IRS strives to produce according to the MTO philosophy. However, some influences of MTS are used to cope with uncertainty; e.g. inventory buffers are used to cope with demand, production and supply uncertainty. Hence, a hybrid production system is used, particularly to cope with the uncertainty in demand (Deleersnyder, Hodgson, King, O'Grady, & Savva, 1992). The production system is similar to a flow line (Bertrand, Wortmann, & Wijngaard, 1998), with multiple production lines that are dedicated to specific products. However, it is customary that multiple products are produced on a production line. IRS sees stochastic demand, which changes over time when the due date comes closer. Backorder costs can be considered very high, since creating a production-stop at the OEMs involves very high penalty costs per minute. Since transport can be expedited to IRS's customers, against higher freight costs, these could also be considered as backorder costs. Furthermore, capacity is limited, but is adjustable within a given range against different cost rates (with an optimum efficiency at some point). Additionally, inventory capacity is limited as well, and setup costs (time) are involved, when changing production from one product to another. The assembly line is partly occupied by permanent employees and partly by temporary employees. Temporary employees are easier to fire, but more expensive per time unit, as is generally the case (Buyukkaramikli, Bertrand, & Van Ooijen, 2013).

Management reported several problems regarding the production, which were caused by scheduling errors, and production scheduling (Hiel, 2015; Sneijkers, 2015). According to IRS managers, the production planning process is inefficient, not standardized, unstructured, not robust to changes in demand, and prone to error. Especially, the presence of flaws in the schedule causes many problems in the production process itself, such as lack of components, or difficulties in meeting delivery due dates. Also, over-time work or idle-time of employees is regularly faced in production, which is considered inefficient. Furthermore, the production schedule reacts heavily to changes in demand volumes. This fluctuation in the production schedule is thought to cause additional costs, and causes difficulties in planning of materials, workforce, and transportation.

Related issues, occurring at IRS, to the production planning were reported as well (Hiel, 2015; Sneijkers, 2015; Vollenberg, 2015). Though not directly relevant to this research, these problems are part of the causes and consequences of the malfunctioning of the production planning. The first problem is caused by the ERP system. A new system was implemented in April 2014, but is nowadays still malfunctioning. Besides limited functioning and support of the ERP system, the information provided by the ERP system is not at all times correct due to bugs in the software. Additionally, it does not support planning activities yet. Second, the MRP is related to the production planning, and problems are caused in two directions. Flaws in the production schedules cause shortages on materials, which on its turn causes complications in the production. The other way around, flaws in the material planning occur as well, which makes the production planning infeasible, when components are auto of stock. Third, horizontal integration of information is reported to be insufficient, which causes departments to work within different perspectives.

2.2 Problem Statement

Concluding from the findings in the previous sections, the following problem statement is defined:

The current production planning does not meet IRS's expectations and might cause unnecessary costs, which are due to over-time working, sending workers home, emergency shipments, schedule nervousness, setup losses and inventory costs.

Underlying aspects of this problem are; observed volatile demand rates, under-capacity of the production system, high emergency shipment costs, and obsolete labor. The under-capacity of the system is caused by a lack of knowledge about production system configurations with a high output per time unit. There is argued that the production line is able to operate under lower takt-times, but the physical requirements to change the line to these requirements are currently not known.

2.3 Literature Review

In literature, production planning is often discussed regarding many different aspects, production environments and industries, and considering different hierarchical levels. The production planning problems faced by IRS, as discussed in section 2.1, are considered to some extend in literature. In this section an overview of theory behind production planning and scheduling and a brief outline of solution methods are given. This literature review is based on Bakens (2015), and a meta-analysis of the used literature is included in Appendix C.

2.3.1 Aggregate Capacity Planning

Optimization of the production planning reduces operational costs for a company (Silver, Pyke, & Peterson, 1998). Aggregate production planning is the intermediate-term planning level in which decisions are made regarding, for example, staffing, subcontracting, procurement, marketing and all other forms of capacity planning (Hopp & Spearman, 2000). Aggregate planning is a broad concept that is also referred to as capacity planning or tactical production planning, in literature. Because the planning of workforce is the main focus of this research, also workforce planning, personnel scheduling, shift scheduling, and workforce scheduling relate to aggregate planning in this context. Note, that in literature "planning", most often, refers to an aggregate planning level (strategic or tactical), while "scheduling" refers to a more detailed planning level (operational). Capacity planning, in general, regards the decision to adapt production rate and the shift model, given the flexibility of the production system (Sillekens, Koberstein, & Suhl, 2011; Volling et al., 2013). A good planning model should include four phases, namely; (1) forecasts of demand, (2) translation of this forecast into capacity requirements, (3) development of a capacity schedule to meet these requirements, and (4) control of the real-time execution (Thompson, 1995).

When considering production planning literature, research is executed at different industries. Workforce and capacity planning is studied in the transportation sector, retail, service industries (e.g. Health Care, logistics, etc.), and manufacturing (Boysen, Fliedner, & Scholl, 2009; Maravelias & Sung, 2009; Van den Bergh, Beliën, De Breucker, Demeulemeester, & De Boeck, 2013; Volling et al., 2013). However the principles of capacity planning are similar in general, the specific characteristics of each situation might require different approaches. Moreover, within the automotive industry various studies have focused on production planning and scheduling, although less research focused on suppliers within the supply chain than on car manufacturers. However, research in this area is limited (Volling et al., 2013); several researches studied similar production settings, which are addressed below.

The capacity allocation problem that Beliën, Demeulemeester and Cardoen (2009) face, in a case study at a hospital, is very similar to most scheduling problems in a manufacturing environment. They developed a multi-objective mixed-integer linear programming (MILP) model that maximizes resource utilization and schedule robustness. In the study multiple “production” stations are considered with numerous operators, constrained by the maximum station capacity and inventory buffer capacity. Teo, Bhatnagar and Graves (2011) study a similar situation in an MTO production environment, particularly focusing on queue length in a stochastic demand environment. A Non-linear programming model, in combination with a simulation model, is developed to improve the MPS. They optimize the workforce capacity requirements, while reducing costs for work-in-progress (WIP) inventory and end-item backorders penalties.

In the automotive industry several researches have focused on capacity planning and scheduling, but most attention is paid to car manufacturers. Volling and Spengler (2011) studied the order scheduling in the MTO environment of a car manufacturer. They developed a mathematical simulation model that aimed at increasing customer service levels and leveling resource utilization, while minimizing inventory- and labor costs. The problem is constrained by a limited production capacity. In addition, Barlatt, Cohn, Fradkin, Gusikhin and Monford (2009) developed a mathematical programming model to reduce total costs of a MTO production system at a car manufacturer. In this study the use of composite variables was examined to reduce complexity of modeling, such as non-linearity. They considered static, deterministic demand, while demand fulfillment is mandatory. Furthermore, legal labor requirements and changeover-times are incorporated in their model, to create a feasible production schedule with minimized labor and inventory costs. Also, Körpeoglu, Yaman and Aktürk (2011) conducted a research at a car manufacturer (MTO environment) in Turkey. They developed two multi-stage stochastic programming models, a non-linear model and a relaxed linearization of the model, to optimize production costs, while assuming finite production capacity, controllable processing times and multiple demand scenarios. Inventory costs are not included in the modeling, while the possibility of backlogging orders is modeled.

Another option to increase capacity is by means of the acquisition of contingent workers. Alp and Tan (2008) developed a dynamic programming model that included the option to hire contingent workforce capacity on top of the permanent crew, in a theoretical study. Furthermore, the option to schedule over-time is incorporated in the model. Also, the cost of hiring capacity (i.e. permanent and contingent employees) is modeled explicitly. When considering minimization of workforce capacity in particular, Buyukkaramikli et al. (2013) argue that it might be advantageous to hire contingent capacity to cope with fluctuation in demand, in their mathematical optimization approach. Especially, when costs of contingent workers are close to the costs of permanent employees, significant costs reductions could be achieved, in an MTO environment. However, when contingent crew costs increase, their model tended towards hiring more permanent employees. Moreover, Easton (2014) considers the option to schedule workforce size a week in advance, in his research in the service sector. In the developed stochastic programming model the option to schedule extra (or less) capacity is examined, showing that the training and use of cross-trained workers is favorable over the use of specialist workers.

Lastly, two researches are presented that are closest to the production planning problem that IRS faces. Sillekens et al. (2011) developed a MILP model focusing on workforce flexibility in an MTO production environment at a car manufacturer. This model includes many legal workforce constraints and the possibility to schedule working times in a flexible manner. Furthermore, the costs of hiring and dismissing of workers is included, as well as labor costs, inventory costs, and changeover costs. Furthermore, the model is constraint by inventory- and production capacity, while assuming that a limited number of production capacity scenarios are available to adjust capacity. The characteristics modeled in this article are the closest to the characteristics of the IRS problem. The model of Sillekens et al. (2011) is extended by the research of Henig, Rieck and Zimmermann (2014). The possibility to schedule production with different cycle times is added, which is similar to the situation of IRS, and the model includes the possibility to schedule for multiple assembly lines.

2.3.2 Planning Solution Methods

In general, several methods to cope with a planning problem are known. The most fundamental method, referred to as conceptual models, is the use of physical characteristics of a production system to cope with uncertainty in the production process, such as yield factors, safety stocks, or over-planning (Mula, Poler, García-Sabater, & Lario, 2006). Furthermore, mainly three groups of quantitative modeling tools exist; analytical models, simulation models, and artificial intelligence based models (Cardoen, Demeulemeester, & Beliën, 2010; Mula et al., 2006). Depending on the characteristics of the problem, different variants could be used to solve the production planning problem (e.g. mathematical programming or stochastic programming in the analytical model group). Peidro, Mula, Poler and Lario (2009) add another group to the mentioned groups, namely hybrid models, that are a combination of the methods, to combine their strengths. All these methods could be implemented in ERP systems (De Sousa, Camparotti, Guerrini, Da Silva, & Júnior, 2014; Framinan & Ruiz, 2010).

2.3.3 Gaps in Literature

Concluding form section 2.3.1, literature has covered many aspects of aggregate planning, though various facets of planning need further attention. In most researches a selection of problem characteristics is made, to focus on a particular feature of a problem. Research has focused on MTS and MTO production environments, the characteristics of different industries, and the results of different solution methods. Nonetheless, the whole complexity of planning and scheduling problems are seldom modeled.

Especially, research within the automotive industry mainly focused on OEMs and to lesser extend on first-tier suppliers. Likewise, studies that depict the influence of (discretely) adjustable production capacity are restricted. Particularly, the interaction of limited inventory capacity, workforce scheduling and the option to put demand in backlog, is not known to the best of our knowledge. Moreover, the influence of workforce allocation to different working stations in a production system, while scheduling, is not researched to the best of our knowledge. Also, research on the modeling of flexibility of capacity is still immature, as is supported by Volling et al. (2013). Specifically, the focus on workforce capacity planning has received little attention, compared to production quantity planning. Likewise, the differentiation between permanent and contingent workers is not widely studied in the automotive sector. Although, many more aspects of production planning are not considered in literature, this is where this research aims to contribute.

2.4 Research Assignment and Methodology

Given the problems faced by IRS, described in this chapter, and the gaps in literature, found in section 2.3, a research topic is specified. The aim of this research is to contribute to existing literature, by providing a solution method for a problem that is not researched yet, and to test and validate it on the IRS case. Additionally, the objective is to improve the production planning of IRS, such that fewer problems are faced and costs are reduced.

2.4.1 Research Assignment

As mentioned in section 2.3, several approaches to different production planning problems are studied, while multiple gaps in production planning literature still exist. Research on the use of flexible capacity is found to be immature. However, many partial solution methods exist on several production planning problems. The option to adjust capacity according to a given set of capacity scenarios is relatively new in literature, however likely to be found in practice. The MILP model that Sillekens et al. (2011) have developed is closest to the production planning problem of IRS. Nevertheless, backorders were excluded from the modeling, and the analysis of production capacity was restricted to capacity scenarios, whereas this study contributes to the composition of the capacity scenarios, by means of allocating operators to working stations.

Since IRS reported problems regarding their production planning, an optimization method is requested to improve their planning method. Currently, seemingly unnecessary costs are made, caused by emergency shipments and labor inefficiency. The MPS is the driver of the production capacity planning, and triggers the daily detailed planning, an optimization tool would most likely improve the quality of the production schedule. The IRS production planning problem is constrained by inventory-, and production capacity limitations. Furthermore, a dynamically adjustable capacity is available to match production capacity and customer demand, as stated in section 2.1. Moreover, a distinction between temporary and permanent workers must be made in scheduling, because they include different costs per time unit. Lastly, the unique capacity of each station in the production system is modeled, which contains the interaction between machines and implicitly exposes bottlenecks in the production line.

These characteristics are, to the best of our knowledge, a unique research setting for the automotive industry. The complexity found in real-life flow line production systems, where production output is limited by the bottleneck machine, becomes especially attractive when there is the option to increase output for each machine. Therefore, when increasing the output of the bottleneck station, another working station becomes the bottleneck. This interaction is explicitly modeled in this research. Constrained by practical limitations, such as inventory- or production capacity, this research's contribution to literature and practice could be significant.

Lastly, literature provides several solution methods to calculate a good or optimal production planning schedules, namely; conceptual modeling, analytical modeling, artificial intelligence based modeling, simulation modeling, or the integration of one of these models into an APS module (Peidro et al., 2009). For this research the most suitable option, to solve the production planning problem of IRS, is analytical modeling, as is supported by Mula et al. (2006). This is the best choice for this situation, since it provides an optimal solution, given the constraints, and is the most understandable method, compared to artificial intelligence based modeling, for the organization. Simulation modeling is very understandable as well, but does not provide equally good results, since the nature of simulation is not to optimize problems, but merely to model and test them. Conceptual modeling could be used to improve the results. The advantages and disadvantages of each solution method are presented in Table 1, and ranked for the IRS case. However, an APS solution would be the most preferable, this is hardly implementable in the short term, since implementation costs are very high and the ERP system of IRS is not ready yet.

The given problem characteristics and available solution methods have resulted in the following research assignment:

Develop a production control methodology for a single, multi-product flow line production system with discrete dynamically adjustable production capacity per working station, constrained by limited production capacity, high backordering costs, and a demand fulfillment requirement.

Table 1: Advantages and disadvantages of production planning solution methods

Solution Approach	Advantages	Disadvantages	Rank
Conceptual Modeling	• Robust to fluctuation • Easy to apply in practice	• Gives only partial solution • No optimization	**3**
Analytical Modeling	• Optimization of problem • Many constraints and objectives to include	• High computational effort • Problem space increases rapidly	**2**
Artificial Intelligence Based Modeling	• Reduces computational effort in complex problems • Copes easily with multi-objective criteria	• Hard to understand • Optimum most likely not found	**5**
Simulation Models	• Visualization of problem • Sensitivity analysis	• Slow computation	**4**
Advanced Planning and Scheduling	• Automatic scheduling with real time monitoring of production and inventory • Provides most likely the best results	• Expensive • A lot of effort involved in implementation	**1**

2.4.2 Research Questions

Resulting from the research assignment, the problem setting, and the available literature, the following research question is constructed;

How can the production planning problem of IRS be improved/optimized, considering fluctuating customer demand and resource capacity constraints on a multi-product assembly line in a make-to-order production environment?

The main research question is supported by several sub-questions;

1. *What is the current situation's performance of the production planning at IRS?*
2. *What are the characteristics of the demand that IRS sees?*
3. *How can the production control policy be improved, including inventory control of finished goods?*
4. *How can the production planning be optimized, standardized and possibly automated?*
5. *What are the benefits of optimizing the production planning?*
6. *How can the findings of this research be implemented in current business?*

2.4.3 Research Scope

Regarding the analysis made in the previous sections, several decisions were made concerning the scope of the research. Decisions are made considering the limitations and of the research. Based on the research questions, the steps that must be made are presented in this paragraph. Besides the development of the general model described above, a validation of that model must be executed by means of the IRS case.

First of all, the size of the research must be restricted to guarantee feasibility of the research project. Therefore, the study focuses on the XC60-Kuga-Mondeo production line. This production line is chosen, since it has seen the most scheduling related problems in the IRS-Venray factory. Furthermore, multiple items for multiple customers are produced on this line, which makes a comprehensive model possible. The aim is to build a generic solution model that is transferable to comparable production systems (including IRS's other production lines). Furthermore, an analysis of the current situation and its performance is made, to compare the improvement's results with the initial system's performance. Additionally, the demand of the customers is analyzed, to be able to adjust safety stock levels of finished goods and for improvement of the production schedule. Next, an optimization model for the problem is developed. This is a mathematical programming model that requires easy implementation in current business practice. The aim of this tool should be to standardize, structure, and automate the MPS planning. Lastly, this planning model is tested with a sensitivity analysis in a case study, and a recommendation on implementation of the findings of the research is included in the study.

This research is mainly divided into three stages; an *analysis phase* (section 3), a *method development phase* (section 4), and the application of the developed method in the *case study phase* (section 5). A more extensive overview of the methodology of the research and the data that is used for the research is given in Appendix D.

3 Detailed Analysis

To be able to develop a production control methodology and measure improvements that are made by the production planning tool, an analysis of the current situation of IRS is needed. This analysis serves as a baseline measure and helps understanding the limitations and constraints of the planning model. Several topics regarding the production planning are highlighted in this chapter. First, an analysis of the characteristics of the production system will be made in section 3.1. Also, the characteristics of the planning process are given in this section. Next, an overview of the demand that IRS faces is given in section 3.2. Lastly, in section 3.3 an overview is given on the current performance of the IRS production system. This serves as a baseline measure to be able to compare with this study's results.

3.1 Production System and Planning Characteristics

To provide an understanding of the exact problem a detailed evaluation of the production system and the planning process is given in this section. This is needed to understand the requirements and constraints that need to be addressed by the planning methodology. First, an overview of the production system is given. Thereafter the production planning process is analyzed.

3.1.1 Production System

The IRS-Venray plant consists of multiple production lines, which are all assembly flow lines. Since the focus of this research is on one production line, the specifics of that line are highlighted in this section. The characteristics of the production system determine the requirements, limitations and assumptions for the modeling, later in chapter 4.

3.1.1.1 Production System Lay-Out and Operator Requirements

This study focuses on one assembly line of the IRS Venray plant; the XC60-Kuga-Mondeo-line (hereafter assumed to be the logical assembly line when referred to in any form). This assembly line produces a Volvo XC60 roof system for a customer with two plants, located in China and Belgium, and two different roof systems for a customer located in Spain, namely a roof system for the Ford Kuga and the Ford Mondeo. The production lay-out for the different products is almost similar, however the production process differs. The three roof systems are different products, with their own specific designs and thus their own specific components. Therefore, the assembly order of components might differ to some extent between the roofs, while certain assembly procedures are specific for one roof. For example, the sliding mechanics of the roofs differ and have a different attachment procedure. For the Ford roof systems the sliding mechanic is mounted to the frame on the assembly line, while for the XC60 roof system it is mounted on the frame in the frame station.

First, to get a good understanding of the assembly of a roof system, the lay-out of the production line is given in Figure 4. Note, that the (dedicated) glass bonding station is not included in this figure, since this is not incorporated in this study. The assembly process contains the following stages; first, the frame of the roof system is made on the frame station. Second, the roof system is assembled and finished in the main assembly line. Next, the quality of the roof is checked in, first, the audit booth by an auditor and, second, at the end of line station (EOL) by a robot. When quality is approved, the roof systems are packaged and moved to the outbound warehouse, ready for shipment. In case the quality of a roof system is below expectation, the roof system is repaired in the repair booth and after completion checked again. The production process is supported by one line feeder and one line coordinator (represented by the orange person in Figure 4), which is the floor manager of a production shift.

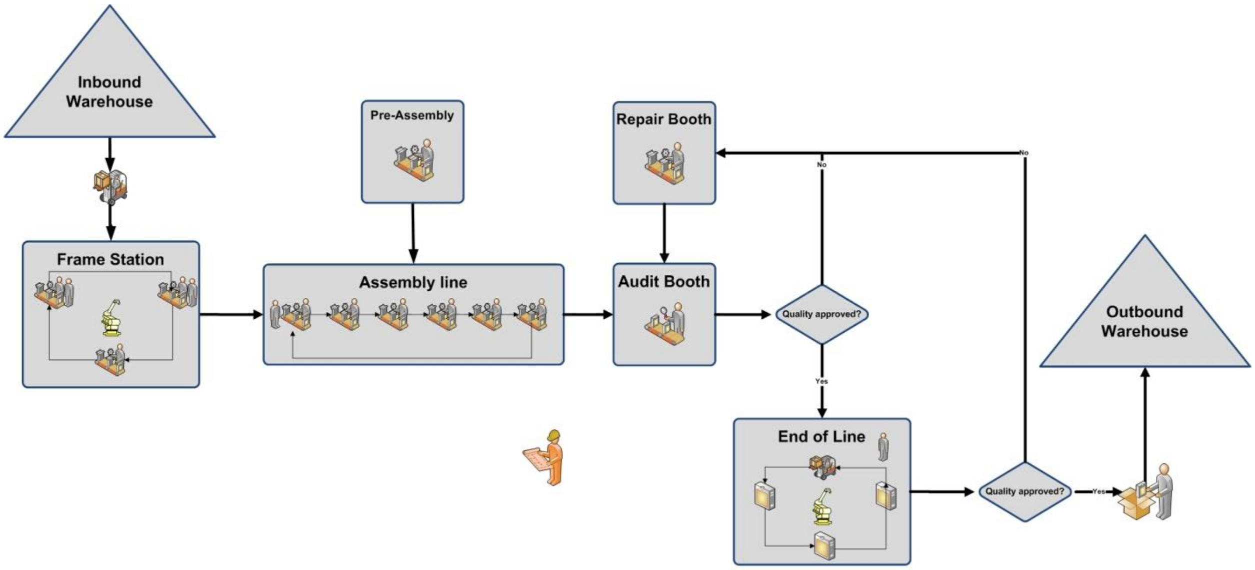

Figure 4: Production process of XC60 vehicle roof systems (China) including the number of operators per shift

First, when production of any type of roof system is started, a changeover process has to be executed when switching from one product to another. This takes approximately 30 minutes per changeover. In this process the tools that are used for the assembly have to be replaced, since these tools are dedicated to a specific product. Furthermore, components that are used for the previous product have to be stored and new components have to be supplied to each station. Furthermore, software programs of the robots in the frame station and EOL station must be changed for the new product, such that the right frames are built and the correct measures are performed. Each operator is responsible for the changeover process of its own station.

Next, the components used in the assembly, for both the frame station and the assembly line are replenished from the inbound warehouse by the line feeders (represented by the forklift truck in Figure 4). The line feeder is responsible for the availability of components at each station, such that stations never run out of work, due to a lack of components. Components are required by the frame station and the assembly line. Furthermore, line feeders do some minor pre-assembly work (for example, clicking a tube on a frame part) and re-works on components (to prevent components to cause quality issues). The most of the pre-assembly work is executed by an operator that provides parts to the different stations in the assembly line.

The frame station is a semi-automated circular conveyor-belt that contains three manned stations. At the working stations operators provide the assembly robot with the required parts, such that the robot can bolt the parts of the frame together. At the last station, the completed frames are placed in racks, as a work-in-progress buffer for the assembly line. The frame station is occupied by 3 to 5 operators for three permanent stations. The maximum output of the frame production is limited by the speed of the robot.

Thereafter, the completed frames are placed on carriers, which are the equivalents of a conveyor belt. At the first working station in the assembly line a frame is put on an empty carrier to be able to start the assembly process. The assembly tasks are performed while the roof system is positioned on the carrier. The carriers, in combination with the tools of the working stations, secure the accurate assembly of the roof system. The carriers move from station to station throughout the assembly line, where each operator manually executes the station specific assembly jobs. The assembly line is currently occupied by 6 or 7 operators, but the number of stations is adjustable by combining or separating tasks, as is depicted in Figure 5. All tasks performed in the assembly line vary from bolting guides to the frame, placing and fixing the glass in the right position, to applying seals and covers. Dividing the jobs over a station is simply allocating a number of tasks to a station, such that the desired throughput time is reached. It is important to keep in mind that most tasks must be executed in a fixed sequence. The duration of each task differs and a single task cannot be split over two stations. Consequently, an optimal division, of tasks over a number of stations to reach a desired throughput time, is limited by the number of tasks and the length of the tasks. Furthermore, the space on the factory floor is limited, and therefore the number of operators that can be employed is limited in the assembly line, implying that production capacity of the assembly line is limited.

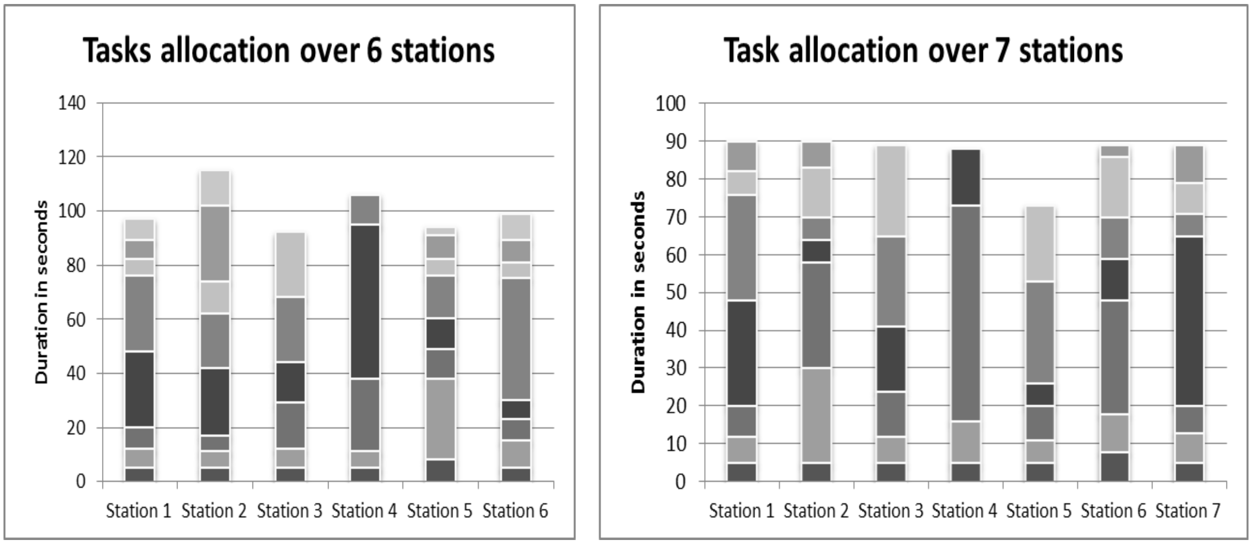

Figure 5: An assembly line task division with respectively 6 and 7 working stations

When the roof system is finished, an operator executes an audio-visual check in the audit booth. The quality of the roof is assessed in terms of visual imperfections, such as scratches, or undesired noises, and on completeness of the roof system (e.g. all components are assembled in the correct manner). When the roof system is approved it can be assessed by the EOL station, elsewise it is repaired and checked again. Currently, the auditing is performed by one operator.

Approved roof systems are now placed on the EOL station by an operator, which is an automated circular conveyor-belt that assesses the roof systems on dimensional correctness, test the safety systems of the roof system, and checks on the presence of certain parts. This is done by means of robots and sensors. After the tests, the roof system is removed from the EOL and packaged when all tests are satisfied. Elsewise, the roof system must be repaired in the repair booth. The operators at the EOL station are responsible for the support of the EOL robot and packaging of the roof systems. The maximum throughput is limited by the speed of the measuring processes. This station is currently occupied by 1-3 operators and one operator for the repair booth. The repair booth is a cabin in which roof systems with defects can be repaired such that they can be sold.

To summarize the total number of workers that are currently required to produce a roof system the total number of FTE (full time equivalent) per roof system is given in Table 2. These numbers are used in the current production process and can be changed when a capacity change is desired. In the production process all tasks must be performed. Hence, it is not possible to remove a function from the process. However, multiple tasks can be allocated to one operator, resulting in a lower output with fewer operators in the system, and vice versa.

Table 2: Number of Employees required for the production of a roof-system per shift

Type	XC60 (Belgium)	XC60 (China)	Kuga	Mondeo
Frame Station	5	5	3	3
Pre-Assembly	1	1	1	1
Assembly Line	7	7	7	7
Audit Booth	1	1	1	1
EOL	1	3	2	2
Repair Booth	1	1	1	1
Line Feeder	1	1	1	1
Line Coordinator	1	1	1	1
Total FTE	**18**	**20**	**17**	**17**

3.1.1.2 Product Differentiation

The roofs produced on this production line are mainly the same in design and functionality. Nonetheless, differences between the roof systems in design and packaging exist. These differences result in dissimilar production processes and thus in different behavior of the production systems, regarding throughput time and the number of operators that are required to produce a roof system. The biggest difference appears in the design of the XC60 roof system and those of the Ford roof systems. The differences in design cause the production processes to have different orders of production tasks and this results, as mentioned above, in different production output.

The production configurations given above expose the differences between the roof systems produced on the production line. The need for the distinction between the two XC60 roof systems is due to a difference in packaging of the finished roofs. The roof systems for Belgium are packed in racks that are less labor intensive, while the packaging for the XC60 roofs to china are packed in cardboard boxes with polystyrene foam. This packaging requires two operators to place the roof system in the correct manner in the boxes, such that the roof systems will not be damaged during transportation.

The difference between the two Ford roofs is mainly the size. The production processes are very similar. Also, the throughput of the system and the number of operators needed to build the Kuga and Mondeo roof systems are equal. Both roof systems are packed into similar racks (except for the size) and shipped to Spain.

As mentioned above, and depicted in Table 3, the production output is dependent of the different roof systems. The XC60 is produced at a rate of 28.5 roofs per hour on average, while the Kuga and Mondeo roof systems have an output of 23.4 roofs per hour on average. These numbers are currently used by IRS management as capacity indicators. These figures are based on experience. Technical downtimes, quality rejects, and production changeovers are implicitly incorporated in these numbers. When analyzing the outputs of the different roof systems, it becomes clear that the XC60 roof systems and the Kuga and Mondeo systems are similar in terms of production output.

Table 3: Production capacity characteristics of the production line

Type	FTE	Output shift	Throughput per hour
XC60 (Belgium)	18	204	28.5
XC60 (China)	20	204	28.5
Kuga	17	168	23.4
Mondeo	17	168	23.4

When considering the total production cycle time for the products, the whole production process must be regarded, as shown before in Figure 2 in section 1.1.2. The most time spent in the production system for a roof system is in the inbound- (components) and outbound (finished goods) warehouse and while the glass is drying after the glass bonding process. These drying times are 4 hours for the Kuga and Mondeo roof systems and 24 hours for the XC60 roof systems. The WIP buffer of glued glasses is kept as low as possible. The assembly tasks take about 15 minutes in total, without time spent in queues. Queue time of the products can be neglected for practical reasons.

3.1.1.3 Quality Rejects and Technical Downtime

The theoretical maximal production output does not represent the realistic output per period. Output is in practice suppressed by downtime of the production system, due to technical failures, and by the rejection of products with insufficient quality. Technical failures are fixed after a period of time and qualitatively insufficient products are repaired and in the end sold. Consequently, both phenomena suppress average output, since downtime reduces net production time, while product rejection causes less output per time unit.

In Figure 6 the average percentage of quality rejects per roof type is given. Note, that the roof systems are allocated into two groups (XC60 and Kuga-Mondeo), since these are production wise similar processes. The overall average reject rate is 16.98% for the Kuga-Mondeo roof systems and 6.00% for the XC60 roof systems.

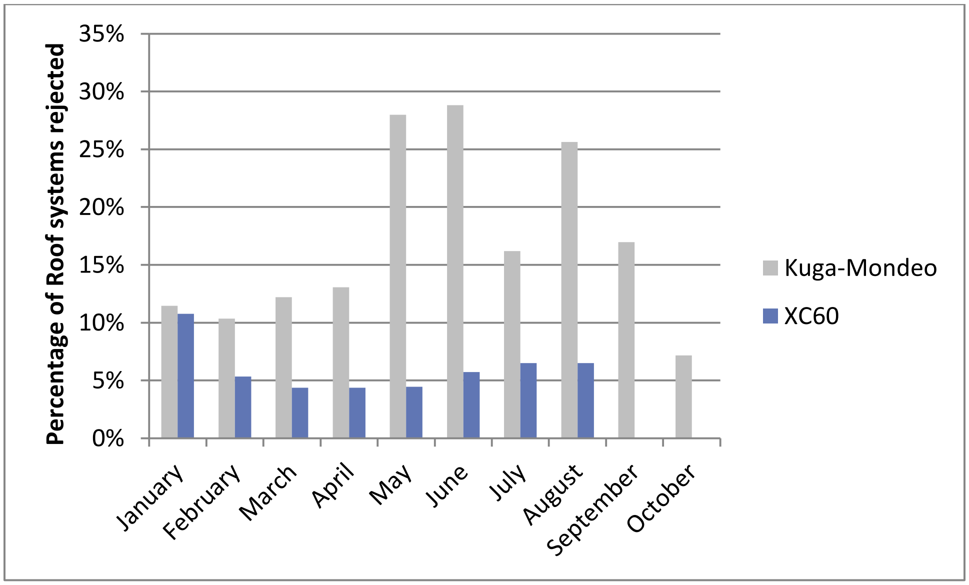

Figure 6: Average percentage of quality rejects per month

In Figure 7 the average downtime per roof system group is given per month. The overall averages are 5.18% downtime for the Kuga-Mondeo roof systems and 3.20% downtime for the XC60 roof systems.

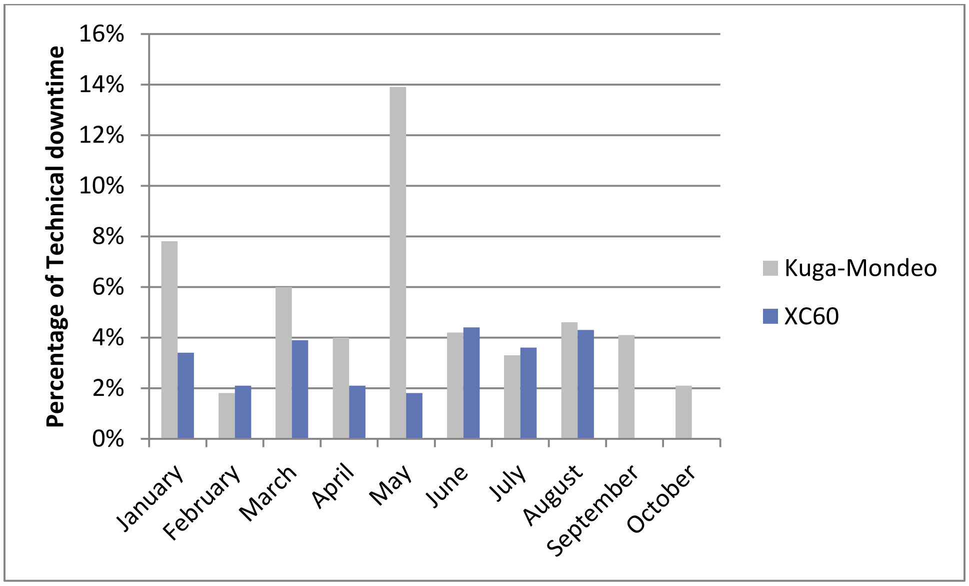

Figure 7: Average percentage of technical downtime per month

3.1.2 Production Planning Process

In the production planning process many factors influence the final planning. Customer orders (forecasts), current inventory levels and available production capacity are the main forces in production scheduling. Hence, these are the inputs for the master production scheduling. Currently, the production planning is completely executed by manually by the production planning department.

3.1.2.1 Current Planning Process

The European planning department is occupied by 2 MPS planners and 4 MRP planners. The MPS that is made is the input for the MRP planners to order components for production. Despite that the MRP planning is executed by the ERP system and those planners solely have to check the MRP planning and place the orders, the MPS planning is done manually. The MPS schedule is solely based on the height of the finished good inventory at the end of a planning period; one week. The end-inventory of a week is currently supposed to be between 1.6 and 3.2 days of safety lead time, based on the average forecasted demand of the upcoming 4 weeks. Why the bandwidth of safety lead time is set on 1.6 to 3.2 days, or whether these are the correct figures, is unknown. Certainly, the safety lead time parameters are not based on the demand characteristics or other forms of uncertainty, such as transportation lead time or production reliability. While making the MPS planning other cost parameters are neglected; labor costs are not included and the cost of hiring or dismissing workers is disregarded. This implies that the scheduled production quantities try to follow the demand fluctuations, however this volatility is tried to be reduced according to the planner’s judgment. Lastly, the planning process is very labor intensive, as mentioned in section 1.1.3, and error prone due to the many manual steps that are taken to process the data.

3.1.2.2 Capacity Scenarios

Currently, capacity scenarios are used to adjust the production output. These capacity scenarios are pre-set scenarios in which a certain number of workers (per shift) is associated with a given output (per shift). An example of a capacity scenario per roof system type is given in Table 3. The output of the production line can be adjusted by adding or subtracting workers of the production system. The different capacity scenarios are chosen by allocating a number of workers in a logical manner over the working stations in the production system. However, when analyzing the production system (Figure 4), mainly four aggregate production stations exist; the frame station, the assembly line, the audit booth, and the EOL. The other workers can be considered as indirect labor; line feeder, pre-assembly, repair booth, and line coordinator. The goal behind the capacity scenarios is, currently, to balance the outputs of the production stations, where the output of the bottleneck station is the output of the line.

3.1.2.3 Output of the Production Planning

The main outputs of the MPS are the production quantities per week, the number of workers required per week, and the end-inventory of finished goods for each week during the planning horizon. These weekly numbers are then allocated over the production days in each week, such that the MRP planners can schedule component orders. Also, production uses the MPS as an indication of what to produce in the future. For the first upcoming four weeks a detailed daily schedule is made that allocates production quantities and workers to specific shifts.

3.2 Demand Characteristics

The different roof systems see their own demand patters, which are depicted in Figure 8. The shown demand volumes are the cumulative weekly demand numbers that were ordered by IRS's customers. An extensive analysis is provided in Appendix E. The main results are summarized in this section.

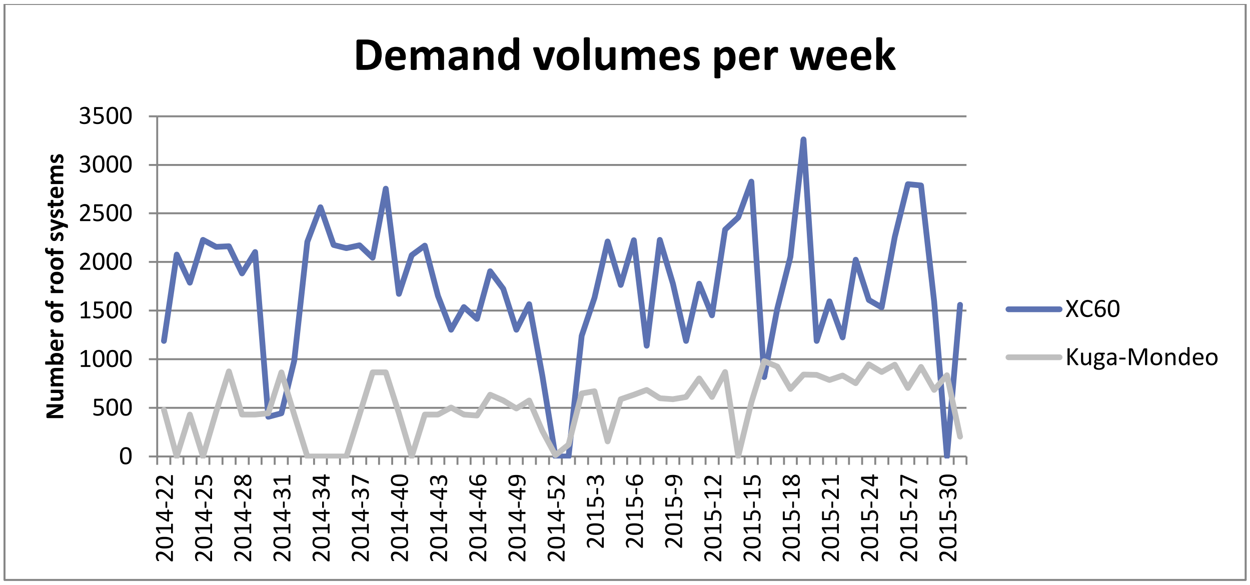

Figure 8: Weekly demand volumes of the XC60- and the Kuga-Mondeo roof systems

Analysis shows that the average weekly demand for XC60 roof systems is 1721 (*S.D. 682*), while the demand for Kuga-Mondeo is 535 (*S.D. 295*) roof systems per week. However, customer factories are closed, due to holidays, for some weeks during a year. When considering the closing of the customer's plants, to show more realistic demand volumes, the average weekly demands are 1809 (S.D. 575) and 623 (S.D. 220) roof systems, for respectively XC60- and Kuga-Mondeo roof systems.

Furthermore, the demand volatility is examined, which is an important characteristic in production planning. Demand volatility is the change in demand volume for a given week throughout the planning horizon. Since customers provide IRS with their demand forecasts, the demand volumes for a given week can be altered at any given time. Consequently, when IRS updates the MPS schedule, the demand volume for a given week is often changed. This volatility causes uncertainty in demand, instead of facing deterministic demand. However demand shows to be very volatile over the planning horizon, the demand average is stable (-1.4% during the planning horizon). This implies that demand volumes change during the planning horizon, but merely interchange between weeks. Consequently, final demand volumes show to be stable when considering long-term demand. Demand appears to be mostly expedited or delayed by IRS's customers, rather than truly cancelled or raised. Therefore, it might be advisable to disregard short-term changes and focus on long-term trends.

Lastly, the demand was checked for normality, in order to be able to calculate safety stock levels for finished goods in section 5.1. All demand is found to be normally distributed; XC60 demand, Kuga-Mondeo demand, and total demand shows a demand pattern according to the normal distribution.

3.3 System Performance

The system performance of the XC60-Kuga-Mondeo production line is described by redundant system costs, regular system costs and re-planning stability. However, due date delivery performance would normally be another performance measure; true backorders are not allowed by IRS management and consequently practically do not occur. This is due to the high penalties that are given to first-tier suppliers by the OEM when they cause a production stop at the OEM. In the section the main findings of the system performance analysis are summarized, which are elaborated in Appendix F.

Redundant costs are made when orders are at the verge of being overdue, which causes a production stop at IRS's customers. Since these production stops result in high penalties, IRS chooses to expedite orders, by means of emergency shipments, or over-time is worked during the weekends. The redundant system costs are measured between week 1 and week 31 of 2015 and were reported to be €84,436 on emergency shipments, and €89,006 on over-time working. This is respectively 4.09% and 4.71% of the total system costs.

However the redundant system costs are desirable to reduce, it is not possible to include these costs in the simulations that are performed in the case study in chapter 5. Therefore, the regular system costs are analyzed for the testing period (week 37-47 of 2015). The costs are standardized, such that they can be compared to the results of the simulations in section 5.5. The costs were standardized by the use of the capacity scenarios (see Table 10) that are used for the case study. The registered production quantities that were planned and produced in this period are assumed to be produced in workforce configurations according to the capacity scenarios. Furthermore, inventory in this period was measured and the hiring and dismissal of contingent workers is retrieved from the difference in the workforce size between the weeks for the assumed capacity scenarios. This resulted in a standardized total system costs for the testing period of €816,700.

Lastly, the re-planning stability was measured, which is defined as the change in production quantity for a given period during the planning horizon. The change in planning should be as little as possible, since it eases the planning of workers and raw materials in terms of availability. Analysis shows that the schedule stability is better than the demand volatility. However, when considering the flatness of the production schedule (*the difference in final production quantities between consecutive weeks*), it is shown that the production schedule is not as flat as would be desired by the IRS management and could be improved (see Figure 9).

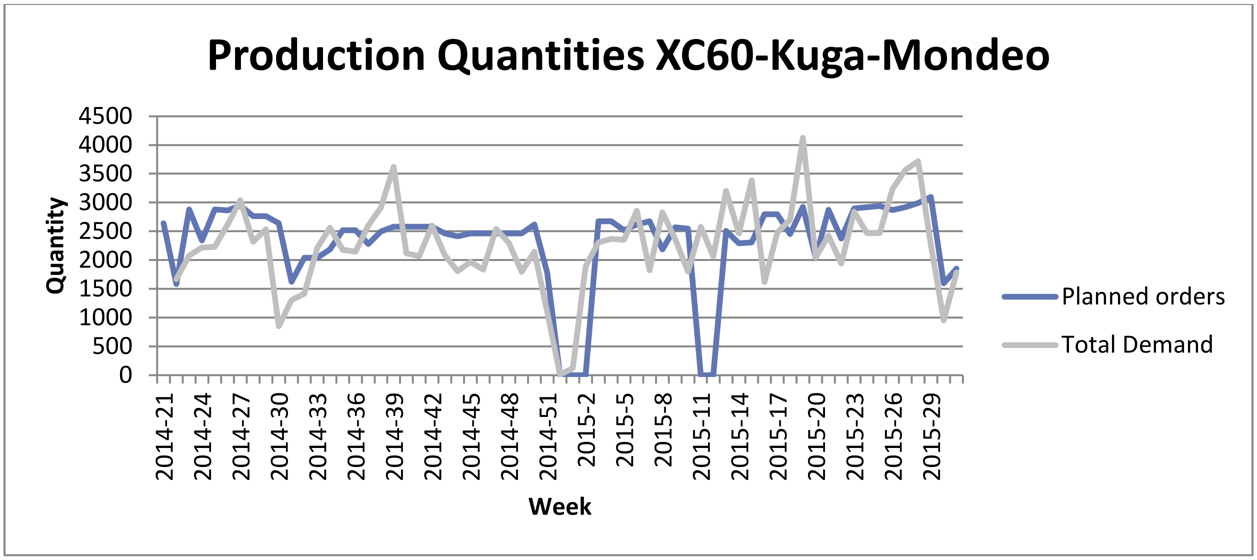

Figure 9: Definite total production quantities scheduled by IRS compared to the total demand

The re-planning stability is measure in term of mean re-scheduling error (MRSE) mean absolute re-scheduling deviation (MARSD). These measures are based on the mean forecasting error and mean absolute deviation, explained in Appendix E. The MRSE measures the average change in production quantities between the first week of scheduling, for a given week, and the final scheduled quantity. On the other hand, the MARSD describes the average absolute fluctuation of the schedule over the planning horizon. This represents the absolute stability (volatility) of the production schedule. The MRSE was 0.7 and the MARSD was 5.8, during the testing period.

4 Method Development

Given the needs en characteristics of IRS and the gaps in literature, an aggregate capacity planning model is built. The mathematical models built in this chapter are built for a general use in environments similar to those of IRS, and later in this thesis tested on the IRS case. We want to provide insights in the (workforce) capacity planning of a first-tier supplier of, for example, the automotive industry, to match demand with production output, given a flexible allocation of workers and a flexible production capacity in a flow line assembly line with multiple stations $\boldsymbol{J}$, multiple products $\boldsymbol{I}$, and/or multiple customers.

Demand $\boldsymbol{D_{i,t}}$ is given per period for a given planning horizon $\boldsymbol{T}$, by means of customer forecasts. Every period the planning is updated, for the same period, minus the last period and including one new period at the end of the planning horizon. Customer demand forecasts for a given period, tend to change after re-planning and consequently the production schedule might need adjustment.

The main variables of the planning model are labor, inventory, backorders and demand. As for each planning method, the goal is to minimize system costs, while meeting demand $\boldsymbol{D_{i,t}}$ as much as possible, and optimizing the balance between inventory $\boldsymbol{s_{i,t}}$ and workforce- and/or capacity costs. When production capacity and inventory are not sufficient to fulfill demand in a period, the remaining orders are put in backlog $\boldsymbol{b_{i,t}}$, against penalty costs.

Furthermore, the assembly line contains multiple stations that have their own characteristics in terms of number of required operators and output $\boldsymbol{P_{i,j}}$ per time unit. Since production is executed in sequence, the bottleneck station of the assembly line limits the output of the system $\boldsymbol{P_{i,t}}$; the output of the station with the least output, is the maximum output of the station. Hence, it is the challenge to balance the output of the individual stations as much as possible, while remaining able to meet the demand.

The production system has an amount of permanent workers $\boldsymbol{w^p}$, and can hire capacity, by means of contingent workers $\boldsymbol{w_t^c}$, from an ELSA. New workers have to be trained however. The training of a worker requires an experienced worker to teach the basics of the assembly tasks. Therefore, the new worker is scheduled double with an experience employee and during the training period $\boldsymbol{\theta}$ the worker does not contribute to the production output. Contingent employees can be hired $\boldsymbol{h_t^c}$ for shorter periods of time, dismissed easier $\boldsymbol{d_t^c}$, but are more expensive than permanent employees. The hiring and dismissing of workers is accompanied with costs. Since the production line is an assembly line and is therefore labor intensive, an increase in number of employees allocated to the system increases the output of the system per time unit. The manner of allocation $\boldsymbol{a_{i,j,t}}$ of workers to the production stations defines the output of the system. The allocation of workers to a station is limited by boundaries for each station ($\boldsymbol{A_{i,j}^{min}}, \boldsymbol{A_{i,j}^{max}}$). Lastly, a decision on the scheduled production output $\boldsymbol{o_{i,t}}$ of the production capacity must be made, since it might be more beneficial to have a lower resource utilization than dismissing capacity for a short period of time. The most important characteristics of the model are highlighted below:

- The number of permanent workers $\boldsymbol{w^p}$ is decided upon at the beginning of the planning horizon and is fixed.
- The number of contingent workers $\boldsymbol{w_t^c}$ is retrieved from the initial period (t=0) and can be adjusted by hiring $\boldsymbol{h_t^c}$ or dismissing $\boldsymbol{d_t^c}$ capacity.
- During the training period $\boldsymbol{\theta}$, a new worker does not contribute output to the production line.
- The production output $\boldsymbol{o_{i,t}}$ of the production system is bounded by the production capacity $\boldsymbol{P_{i,t}}$.
- All employees in the total pool of workers, permanent workers $\boldsymbol{w^p}$ and contingent workers $\boldsymbol{w_t^c}$, must be allocated to the production stations $\boldsymbol{J}$.

- The minimum $\boldsymbol{A_{i,j}^{min}}$ and maximum $\boldsymbol{A_{i,j}^{max}}$ number of workers allocated to a station is limited by feasibility boundaries (e.g. production space, company regulation, etc.) and have to be determined in advance.
- The interaction between the different output rates per employee per station $\boldsymbol{P_{i,j}}$ is incorporated in the planning model, and thus the efficiency of different allocation scenarios on the production system is taken into account.

In the remainder of this section the goals of the modeling is explained in section 4.1. Next, the parameters, variables, and sets used in the modeling are given in section 4.2. The bottleneck capacity planning model (BCPM) is presented in section 4.3, while a simplification of this model is given in section 4.4. This simplification is made to enhance the practical usefulness for IRS, since the output of the BCPM might be too complex for the daily routines at IRS. However, the BCPM serves as input for the simplified model.

4.1 Goals of the Modeling

Since an aggregate capacity planning aims to match production and demand, while minimizing the total costs of the production system, the goal of the planning models in this study is to find an optimal workforce capacity level for each period within the planning horizon. This should result in an optimal number of permanent employees and an optimized schedule for contingent capacity per period. Furthermore, the BCPM should provide an insight in the behavior of the working stations in the assembly line when they are occupied by different numbers of operators. This should result in good and efficient capacity scenarios that should be included in the simplified IRS model.

To the best of our knowledge, as mentioned in chapter 2, no mathematical model exists that addresses the characteristics discussed above. Therefore, these models aim to contribute to current knowledge and to provide insights in the interaction of different working stations in a production system regarding the aggregate production planning. The mathematical approach that is able to address the needs and complexity of the BCPM is a mixed-integer non-linear programming (MINLP) approach. For the IRS model a MILP is built, since it is a computationally more efficient model, with simpler assumptions and outputs. This approach is chosen, since it enhances the likelihood of implementation of the planning methodology and the roll-out of the methodology throughout the company. Both models find optimal workforce capacity and production quantity levels, given the model's capabilities and limitations. The final aim is to provide insights in the behavior of the parameters that are included in production planning which are the following:

- **Inventory**; putting an upper or lower bound on inventory is likely to change the behavior of the planning and might change the costs of the system. Also, the height of the inventory holding costs is probable to influence the model's behavior.
- **Hiring and dismissing workers;** adjusting costs for hiring or dismissing workers possibly improves or decreases the system's performance. Adding additional penalty costs for dismissing workers plausibly improves workforce planning stability. This could be a company objective, since toying with personnel could be considered undesirable. Lowering hiring (training) costs on the other hand is likely to enhance the use of a flexible workforce, and might expose the benefits of investing in reduced training times for new employees for example.
- **Production capacity utilization;** limiting the utilization of the available production capacity might cause the production system to perform more reliable, especially in practice. Having over-capacity increases the ability of the production system to cope with uncertainty.

4.2 Sets, Parameters and Variables

Sets:

$i = \{1,2,\dots,I\}$; number of items i produced in the production system
$j = \{1,2,\dots,J\}$; number of stations j in the production system
$k = \{1,2,\dots,K\}$; number of pre-specified capacity scenarios k in the production system
$t = \{1,2,\dots,T\}$; number of periods t in the planning horizon

Parameters:

C^p = ***c**ost of a **p**ermanent worker per period*
C^c = ***c**ost of a **c**ontingent worker per period*
C^h = ***c**ost of **h**iring a worker*
C^d = ***c**ost of **d**ismissing a worker*
C_i^s = ***c**ost of **h**olding an item i on stock per period*
C_i^b = ***c**ost of having an item i in **b**acklog per period*
$P_{i,t}$ = ***p**roduction capacity of the system for item i in period t*
$P_{i,k,t}$ = ***p**roduction capacity of the system for item i and capacity scenario k in period t*
$P_{i,j}$ = ***p**roduction capacity for station j per employee*
$A_{i,j}^{min}$ = ***min**imum number of workers that must be **a**llocated to a station to be operative*
$A_{i,j}^{max}$ = ***max**imum number of workers that must be **a**llocated to a station to be operative*
S_i^{min} = ***min**imum level of **s**tock allowed for item i (safety stock)*
S_i^{max} = ***max**imum level of **s**tock allowed for item i (inventory capacity)*
W_i^k = *number of **w**orkers for capacity scenario k for item i*
θ = *training period length for a new empoyee*
M = *sufficiently large number such that constraint cannot be violated*

Auxiliary variables:

w^p = *number of **p**ermanent **w**orkers in the production system*
w_t^c = *number of **c**ontingent **w**orkers in period t*
$w_{k,t}^{tot}$ = ***tot**al number of workers for capacity levels k in period t*
$s_{i,t}$ = *number of items i in **s**tock in period t*
$b_{i,t}$ = *number of items i in **b**acklog in period t*
$D_{i,t}$ = ***D**emand for item i in period t*
$\gamma_{i,t}$ = *binary variable to ensure backlog − stock balance for item i in period t*

Decision variables:

h_t^c = *number of **c**ontingent workers **h**ired in period t*
d_t^c = *number of **c**ontingent workers **d**ismissed in period t*
$a_{i,j,t}$ = *number of workers **a**llocated to station j for production of item i in period t*
$o_{i,t}$ = *scheduled production **o**utput of the production system of item i in period t*
$\rho_{i,k,t}$ = *binary variable to choose capacity scenario; for item i, capacity scenario k in period t*

4.3 Bottleneck Capacity Planning Model

The BCPM is developed to estimate the total number of workers in the system (i.e. for each station) and allocate them randomly to the production stations. This means that no specific worker is allocated to a station, but that a given number of workers is allocated to that station. This results in an output per working station, where the station with the least output (i.e. bottleneck) represents the system output. However, the utilization of the system is allowed to be less than 100%. The workforce each period is composed of the pool of permanent employees and a pool of contingent workers. The number of contingent workers can be adjusted by hiring or dismissing them, while the number of permanent employees is fixed. When hiring employees a training period of $\boldsymbol{\theta}$ weeks is started in which the new operator is not productive. Furthermore, the pool of trained workers results in a maximum capacity $\mathbf{min}_{j\in J}\{\boldsymbol{P}_{i,j}(\boldsymbol{a}_{i,j,t})\}$ for that allocation of workers. The function $\boldsymbol{P}_{i,j}(\boldsymbol{a}_{i,j,t})$ represents the relation between adding an extra worker to a station and the increase in output for that station. This relation is most likely non-linear in practice. For example, the marginal contribution per worker decreases with the increase in number of workers allocated to that station. Additionally, the model is allowed to plan less production output ($\boldsymbol{o}_{i,t}$) than its maximum capacity $\boldsymbol{P}_{i,t}$ for that period, implying that the production system is not always 100% utilized. Note, that $\boldsymbol{o}_{i,t}$ is a decision variable that is bounded by the planned maximum capacity. This might be beneficial when it, for example, is cheaper to reduce inventory costs, by producing less for a short period, than dismissing workers and hire them again for a short period of time. The model plans production quantities per period $\boldsymbol{t}$ over a planning horizon $\boldsymbol{T}$. Lastly, the model accounts for different output rates per station for different items. This implies that production speed might differ per produced product $\boldsymbol{i}$.

The aim of the objective function is to minimize the system's cost by finding an optimum between the decision variables. The labor costs of both permanent and contingent employees are incurred, as well as the costs for hiring and dismissing contingent workers. Furthermore, the costs for holding inventory per period are included. Likewise, the costs for having items in backlog per period are included. Since this model is non-linear, a mixed-integer non-linear programming approach is needed to optimize the problem.

Obj.

$$Minimize\ Costs = \sum_{t=1}^{T}\left(C^{p} \cdot w^{p} + C^{c} \cdot w_t^{c} + C^{h} \cdot h_t^{c} + C^{d} \cdot d_t^{c} + \sum_{i=1}^{I}\left[C_i^{s} \cdot s_{i,t} + C_i^{b} \cdot b_{i,t}\right]\right) \tag{1}$$

S.t.

$$w_t^c = w_{t-1}^c + h_t^c - d_t^c; \qquad \forall\, t = \{1, \dots, T\} \tag{2}$$
$$\sum_{j=1}^{J} a_{i,j,t} = w^p + w_t^c - \sum_{i=0}^{\theta-1} h_{t-i}^c; \qquad \forall\, t = \{1, \dots, T\} \tag{3}$$
$$P_{i,t} = \min_{j\in J}\{P_{i,j}(a_{i,j,t})\}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\}, j = \{1, \dots, J\} \tag{4}$$
$$A_{i,j}^{min} \le a_{i,j,t} \le A_{i,j}^{max}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\}, j = \{1, \dots, J\} \tag{5}$$
$$o_{i,t} \le P_{i,t}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{6}$$
$$s_{i,t} = \left[s_{i,t-1} - b_{i,t-1} + o_{i,t} - D_{i,t}\right]^{+}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{7}$$
$$S_i^{min} \le s_{i,t} \le S_i^{max}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{8}$$
$$b_{i,t} = \left[b_{i,t-1} - s_{i,t-1} - o_{i,t} + D_{i,t}\right]^{+}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{9}$$
$$s_{i,t} \le \gamma_{i,t} \cdot M \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{10}$$
$$b_{i,t} \le (1 - \gamma_{i,t}) \cdot M; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{11}$$
$$d_t^c, h_t^c, w^p, w_t^c, a_{j,t} \in \mathbb{N}; \qquad \forall\, t = \{1, \dots, T\}, j = \{1, \dots, J\} \tag{12}$$
$$s_{i,t}, b_{i,t} \ge 0; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{13}$$
$$\gamma_{i,t} \in \{0,1\}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{14}$$

The objective function (1) aims at minimizing the labor costs for temporary and permanent workers, the holding costs, backorder costs, and costs for hiring and firing employees. Constraint (2) defines the total pool of contingent employees per period. The number of contingent workers is equal to the number of workers in the previous period plus the hired contingent workers in this period, minus the number of dismissed contingent employees. Constraint (3) ensures that all trained workers are allocated to a production station, such that no employee is idle. The contingent workers that are still trained are disregarded for the allocation, since they are not productive until their training is finished. (4) describes the relation between system output and station outputs; the station with the lowest output determines the system output. Furthermore, constraint (5) ensures that the number of workers at a station is a feasible scenario. This might be a restriction on the number of workers due to a limited machine speed or a limited space. The least number of workers can be constrained, because two operators are needed to perform a task, for example. Therefore, the minimum and maximum number of operators that can be allocated to a station should be based on practical limitations and policy. (6) guarantees that the planned production quantities cannot exceed the production capacity. Note, that both, $\boldsymbol{o}_{i,t}$ and $\boldsymbol{P}_{i,t}$ are based on decisions variables and interact via this constraint. Constraints (7-11) define the inventory balance equations and inventory restrictions. Inventory can be bounded by means of safety stock or warehouse capacity, for example. Both, inventory and backorders are auxiliary decision variables, since this alleviates computational effort. Lastly, (12-14) ensure logical, non-negativity, and binary constraints.

4.4 Simplified IRS Model

In this section a simplified version of the BCPM is presented. This simplified model is developed to enhance practical usefulness of the model for IRS. The BCPM is too complex in terms of computational effort and in terms of the format of the output. For example, stakeholders within the organization require a number of workers that is needed per period, instead of the allocation of a certain number of workers to a specific production station. Also, the use of capacity scenarios $\boldsymbol{k}$ is preferred by the IRS stakeholders, since it is in accordance with the current planning- and production process. In conclusion, the simplified model is developed to satisfy two goals; the model should be practically useful and easy to use, and the model should provide good results with little computational effort.

Therefore, the IRS model is based on the BCPM and should use the theory of the BCPM to create good and efficient capacity scenarios. The main benefit of the BCPM is that it is able to model the interaction between working stations, and hence implicitly creates good and efficient capacity scenarios. Such a scenario is an allocation of workers over the working stations in the production system, such that idle time of workers is minimized. For the BCPM to provide good capacity scenarios, the marginal contribution per worker $\boldsymbol{P}_{i,j}(\boldsymbol{a}_{i,j,t})$ should be known. However, this is not the case for the IRS production system. It proved infeasible to obtain reliable information about the behavior of the working stations in the system, when increasing or decreasing the number of workers. Therefore an assumption about the worker's contribution function $\boldsymbol{P}_{i,j}(\boldsymbol{a}_{i,j,t})$ is made. The capacity scenarios that are used by the IRS model contain information about the output $\boldsymbol{P}_{i,k,t}$ and the number of workers $\boldsymbol{W}_i^k$ required per scenario $\boldsymbol{k}$.

Capacity scenarios are selected based on a binary decision variable $\boldsymbol{\rho}_{i,k,t}$. This decision variable is used to select the best capacity scenario $\boldsymbol{k}$ for each period in such a manner that the production planning is optimized over the whole planning horizon $\boldsymbol{T}$. Although the efficiency of each scenario is different in terms of output-per-worker, the labor costs account for this phenomena and the model aims at choosing the most efficient capacity scenario whenever possible.

Besides the use of capacity scenarios, the IRS model does not allow for backorders, in contrast to the BCPM, despite the fact that there is the option to expedite transport by means of emergency shipments, and hence extend the due date. IRS management does not allow for backorders, since backorder penalty costs are very high when a production stop at IRS's customers is caused due to delayed deliveries of IRS. Emergency shipments are currently used as last buffer when, for example, production problems unexpectedly arise. In case these would occur in a period in which backorders were planned, the costs would be unacceptable, and thus the choice is made to disregard backorders. However, a big number could be used for the backorder penalty costs, to prevent for the scheduling of backorders, it is chosen to exclude the possibility to schedule backorders from the model. Hence, the model is simpler and the computational complexity is decreased. Also, the possibility to limit the maximum amount of inventory is eliminated, since it might negatively influence system performance.

Additionally, the use of capacity scenarios enables the model to become linear. This saves computational effort since it can easily be solved with for example the SIMPLEX algorithm or other linear solvers. This greatly enhances the quality of the output of the model, as well as the computational time required to calculate a production plan. This improves the usefulness and the ability of the model to solve greater and thus more complex problems. Furthermore, the IRS model provides more straightforward information. The model presents the total number of workers that is needed each period and neglects the allocation of workers over the different production stations. This is preferred over the more detailed output the BCPM offers. Likewise, the use of capacity scenarios aligns with the current way of working, and is therefore more desirable.

Summarizing, the main difference of the IRS model with the BCPM is that is disregards the interaction between working stations and replaces it with capacity scenarios. Therefore, the input of correct and good capacity scenarios becomes vital for good output of this model. Moreover, backorders are not allowed in this model. Furthermore, the model is similar to the BCPM; it optimizes the total costs for the planning horizon (permanent and contingent worker salary, costs for hiring and dismissing workers, and inventory holding costs). The model schedules one $\boldsymbol{\rho_{i,k,t}}$ capacity scenario $\boldsymbol{k}$ per period per item, and balances the number of workers by hiring or dismissing contingent workers. The number of permanent employees is fixed. Again, the model is allowed to produce less $\boldsymbol{o_{i,t}}$ than its scheduled available capacity $\boldsymbol{P_{i,k,t}}$. Boundaries on inventory are also included; however no upper boundary for inventory is included. Note, that in this model only $\boldsymbol{o_{i,t}}$ and $\boldsymbol{\rho_{i,k,t}}$ are decision variables, since the number of workers that need to be hired $\boldsymbol{h_t^c}$ or dismissed $\boldsymbol{d_t^c}$ is dependent on the capacity scenarios that are selected for each period.

Obj.

$$Minimize\ Costs = \sum_{t=1}^{T}\left(C^p w^p + C^c w_t^c + C^h h_t^c + C^d d_t^c + \sum_{i=1}^{I}\left[C_i^s s_{i,t}\right]\right) \tag{15}$$

S.t.

$$w_t^c = w_{t-1}^c + h_t^c - d_t^c; \qquad \forall\, t = \{1, \dots, T\} \tag{16}$$
$$w_{t,k}^{tot} = w^p + w_t^c - \sum_{x=0}^{\theta-1} h_{t-x}^c; \qquad \forall\, t = \{1, \dots, T\}, k = \{1, \dots, K\} \tag{17}$$
$$w^p \leq w_{k,t}^{tot}; \qquad \forall\, t = \{1, \dots, T\}, k = \{1, \dots, K\} \tag{18}$$
$$\sum_{i=1}^{I}\left(\rho_{i,k,t} W_i^k\right) = w_{k,t}^{tot}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\}, k = \{1, \dots, K\} \tag{19}$$
$$s_{i,t} = s_{i,t-1} + o_{i,t} - D_{i,t}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{20}$$
$$S_i^{min} \leq s_{i,t}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{21}$$
$$o_{i,t} \leq \rho_{i,k,t} P_{i,k,t}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\}, k = \{1, \dots, K\} \tag{22}$$
$$\sum_{k=1}^{k=K} \rho_k = 1; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{23}$$
$$d_t^c, h_t^c, w^p, w_t^c \in \mathbb{N}; \qquad \forall\, t = \{1, \dots, T\} \tag{24}$$
$$s_{i,t} \geq 0; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\} \tag{25}$$
$$\rho_{i,k,t} \in \{0,1\}; \qquad \forall\, t = \{1, \dots, T\}, i = \{1, \dots, I\}, k = \{1, \dots, K\} \tag{26}$$

The objective function (15) aims to minimize total production costs for the system. It optimizes over permanent- and contingent labor costs, costs for hiring and dismissing contingent workers, and inventory holding costs per period. Constraint (16) balances the contingent workforce size, by hiring and dismissal of contingent employees, whereas (17) represents the total pool of trained workers. The total pool of trained workers contains all permanent and contingent employees, but excludes the number of workers that are not yet entirely trained. The number of trained workers is ensured to be equal to the number of workers required for the scheduled capacity scenario. Furthermore, constraint (18) guarantees that the total number of trained workers is equal or greater than the number of permanent employees, implying that permanent employees cannot be dismissed. (19) ensures that the total number of trained workers is equal to the sum of employees required for each capacity scenario for each item, such that all items can be produced. The inventory balance equation and the lower boundary (safety stock) on inventory are given in constraints (20) and (21). Next, the planned production quantity is bounded by the available capacity scheduled, in constraint (22). The scheduled capacity is a result of the output of the chosen capacity scenario. Constraint (23) ensures that exactly one capacity scenario per period is chosen for each item. Lastly, (24-26) ensure logical, non-negativity, and binary constraints.

5 Case Study

The IRS model developed in the previous section is tested and applied on the IRS case in this chapter. Since the BCPM developed in section 4.3 is too complex for practical usefulness, the simplified IRS model, developed in section 4.4, is used for the performance analysis executed in this chapter. The XC60-Kuga-Mondeo production line is used as test case to evaluate different scenarios of planning. As mentioned, this model uses capacity scenarios to model production capacity, does not allow for backorders, has a fixed number of permanent employees, and can adjust capacity by hiring or dismissing contingent workers. The exact values for all variables and parameters are explained in section 5.1 and 5.2. In section 5.3 a summary of the assumptions that are made for the case study is presented, which is a result of the findings in chapters 2, 3, and 4. Next, a description of the procedures that were followed in the case study tests is given in section 5.4. Afterwards, the results of the case study are presented in section 5.5, while a summary and conclusion of the case study is given in section 5.6.

5.1 Variables and Constraints

For the case study several inputs are required; demand data, production capacities, and the initial status of the system at the beginning of the planning period. Furthermore, the total number of permanent en contingent workers must be available, to assess the performance from the starting situation.

Each period is one week in the case study, and each planning horizon is 15 weeks. The re-scheduling frequency is set at one period, meaning that the planning is updated every period. This is similar to IRS practice. The testing period exists out of ten re-scheduling cycles between week 37-2015 and week 47-2015. Week 42 is missing since the production scheduler had a week off. Therefore, the production plan was not re-scheduled for that week. The same goes for the tests in this case study; in week 42 the planning is not made. The first week of the planning horizon is the week that is planned in. Since the planning is mostly made on Wednesday at IRS, the demand and production quantities of that week are less than the original quantities. The first week in the planning horizon is therefore used to react on unexpected events and elsewise not changed. Lastly, it is notable that week 52 and 53 are scheduled vacation periods in which the IRS plant is closed.

5.1.1 Demand

The demand is known to change within given weeks throughout the planning period. This is incorporated in the data that is used for the testing period. The final customer orders are presented in Table 4. The average XC60 demand is 1818 roof systems per period and the average roof system demand per period for Kuga-Mondeo is 862.

Table 4: Final customer orders during the testing period

Week	2015-38	2015-39	2015-40	2015-41	2015-42	2015-43	2015-44	2015-45	2015-46	2015-47	2015-48
XC60	1665	1588	2000	1625	1642	2300	1608	2000	1893	2064	1608
Kuga-Mondeo	1040	1018	783	600	912	360	1020	840	900	972	1040

The volatility of demand for this testing period is given in Table 30 in Appendix G. Again the demand shows comparable volatility in the testing period as analyzed in section 3.2 and Appendix E. The total fluctuation over the planning horizon is relatively small compared to the absolute fluctuation each week. A more extensive overview of the demand characteristics during the testing period can be retrieved from Appendix G.

5.1.2 Production Capacity Scenarios

As discussed in section 4.3, several capacity scenarios could be retrieved from the BCPM. The efficient scenarios would be a result of the minimum of a combination of number of workers allocated over the production stations $\boldsymbol{P_{i,j}(a_{i,j,t})}$ in the production system. However, the behavior of the worker contribution function $\boldsymbol{P_{i,j}(a_{i,j,t})}$ is unknown and most likely non-linear. The best method to estimate the behavior of each production station is to make a linear approximation of the contribution of an operator to that specific station. This approximation is done by assessing the current output of the production stations and dividing it by the number of operators currently working at that production station. The results are presented in Table 5, and can be considered as the slope of $\boldsymbol{P_{i,j}(a_{i,j,t})}$. This means that for each extra operator the output for station $\boldsymbol{j}$ increases with $\boldsymbol{P_{i,j}}$. Also, the minimum $\boldsymbol{A_{i,j}^{min}}$ and maximum $\boldsymbol{A_{i,j}^{max}}$ amount of operators that can be allocated to a working station is presented. Note, that there are always four operators needed that perform indirect tasks (e.g. a line feeder or a line coordinator), such that that there is always enough capacity available to perform indirect tasks and prevent for production stops.

Table 5: Contribution of one operator to the output of a station

Station	**XC60** (items per shift)			**Kuga-Mondeo** (items per shift)		
	$\boldsymbol{P_{i,j}}$	$\boldsymbol{A_{i,j}^{min}}$	$\boldsymbol{A_{i,j}^{max}}$	$\boldsymbol{P_{i,j}}$	$\boldsymbol{A_{i,j}^{min}}$	$\boldsymbol{A_{i,j}^{max}}$
Frame Station	*44*	3	6	*69*	1	3
Assembly Line	*32*	3	9	*28*	3	8
Audit Booth	*230*	1	2	*211*	1	2
EOL	*122*	1	3	*117*	1	3
Indirect Labor	*NA*	4	4	*NA*	4	4

Any combination of operator allocations to production stations can be made now. Appendix H shows the finite number of combinations of capacity scenarios (168 for XC60 and 108 for Kuga-Mondeo) that can be made for the production line. The most efficient capacity scenarios are collected in Table 6 and Table 7. These are the scenarios that have the highest output per given total number of employees. These scenarios are implicitly the most balanced configurations of the assembly line. For example, it is not logical to schedule a production configuration with 14 employees with an output of 96 roof systems per shift, while the same number of workers can produce 128 roof systems per shift in a more balanced configuration. The scenarios that are emphasized in red are relatively inefficient scenarios compared to scenarios with similar outputs, and are therefore dismissed in the case study for practical reasons. The reduction of the number of available capacity scenarios reduces the calculative effort and decreases the complexity of the model. Likewise, we choose to exclude scenarios that were very similar to other scenarios. For example a scenario was excluded that increased shift output by 4 roof systems for adding one more operator to the system. This leaves 8 capacity scenarios for XC60 production and 7 scenarios for Kuga-Mondeo production. All capacity scenarios are given in shift outputs. The IRS production system works currently 15 shifts per week; 10 are allocated to XC60 and the remaining 5 are allocated to Kuga-Mondeo. This allocation of shifts is not changeable, since pre-assembly processes, especially the glass bonding stations, have limited capacity to supply the production system.

Table 6: Efficient capacity scenarios for XC60 roof system production

XC60 shift output											
Capacity Scenario	Audit Booth		EOL		Frame Station		Assembly Line		System Ouput	FTE	Output/FTE
	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j		p^i,j(a^i,j)	w^tot
1	1	230	1	122	3	132	3	96	96	12	8,00
2	1	230	1	122	3	132	4	128	122	13	9,38
3	1	230	2	244	3	132	4	128	128	14	9,14
4	1	230	2	244	3	132	5	160	132	15	8,80
5	1	230	2	244	4	176	5	160	160	16	10,00
6	1	230	2	244	4	176	6	192	176	17	10,35
7	1	230	2	244	5	220	6	192	192	18	10,67
8	1	230	2	244	5	220	7	224	220	19	11,58
9	1	230	2	244	6	264	7	224	224	20	11,20
10	1	230	2	244	6	264	8	256	230	21	10,95
11	2	460	2	244	6	264	8	256	244	22	11,09
12	2	460	3	366	6	264	8	256	256	23	11,13
13	2	460	3	366	6	264	9	288	264	24	11,00

Table 7: Efficient capacity scenarios for Kuga-Mondeo roof system production

Kuga-Mondeo Shift output											
Capacity Scenario	Audit Booth		EOL		Frame Station		Assembly Line		System Ouput	FTE	Output/FTE
	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j	p^i,j(a^i,j)	w^tot	
1	1	211	1	117	1	69	3	84	69	10	6,90
2	1	211	1	117	2	138	3	84	84	11	7,64
3	1	211	1	117	2	138	4	112	112	12	9,33
4	1	211	1	117	2	138	5	140	117	13	9,00
5	1	211	2	234	2	138	5	140	138	14	9,86
6	1	211	2	234	3	207	5	140	140	15	9,33
7	1	211	2	234	3	207	6	168	168	16	10,50
8	1	211	2	234	3	207	7	196	196	17	11,53
9	1	211	2	234	3	207	8	224	207	18	11,50
10	1	211	3	351	3	207	8	224	207	19	10,89
11	2	422	3	351	3	207	8	224	207	20	10,35

5.1.3 Initial System Status

The initial settings of the production system are the same for all tests. In week 37-2015 (*t=0*) inventory contains 528 XC60 roof systems and 504 Kuga-Mondeo roof systems. 995 orders for XC60 roof systems are yet to be fulfilled, while 372 orders for Kuga-Mondeo are still open. The remaining planned production orders are 636 XC60 roof systems and 764 Kuga-Mondeo roof systems. Lastly, 39 permanent workers and 16 contingent workers occupy the production line.

5.1.4 Constraints

Firstly, the training period for new contingent workers is estimated to be one period (i.e. one week). This is similar to practice where new employees are trained for a week. Workers that are in their training period are scheduled together with an experienced employee that teaches one (sub-)station of the production system to the new worker. After this training week the new operator is productive. When a worker is employed for a longer time, he receives more training to learn more production tasks. Costs accompanied with these additional training are explained in section 5.2.

Next, the minimum stock is restricted at IRS. Currently, IRS set the safety stock level on 1.6 days of demand for the upcoming four weeks. Since there are doubts about the correctness of this safety stock level a new safety stock policy is proposed. Since we proved that demand is distributed normally, and we have demand forecasts available, a safety stock policy based on customer forecasts during the planning horizon is proposed. The standard deviation $\boldsymbol{\sigma_t^D}$ of the demand for each week $\boldsymbol{t}$, estimated over the demand in the planning horizon is used to estimate the safety stock each period (King, 2011);

$$\boldsymbol{Safety\ Stock = z_\alpha \times \sqrt{PLT/_t} \times \sigma_t^D = S_i^{min}}$$

In the SS formula above, $\boldsymbol{z_\alpha}$ represents the z-value of the normal distribution that is related to the desired service level $\boldsymbol{\alpha}$. The desired service level used here is 95% ($\alpha = 0.95$), which is based on the ration between backorder costs and holding costs. This calculation is included in Appendix I. However backorders are not allowed in the case study, an estimation of a reasonable service level is made here. In real-life the possibility exists to work overtime or have emergency shipments to fulfill backorders, therefore production stops of the customers can be prevented. The costs for emergency shipments are used to estimate backorder costs, since these are most representable for realistic backorder costs. The SS level is calculated every re-scheduling period $\boldsymbol{PLT}$ (*planning lead time*) and thus adjusts for change in demand patterns (i.e. trends). We found this method to be preferable over a fixed safety stock level calculated over a longer period of demand, since it is more flexible.

5.1.5 Summary of Input Parameters

A summary of the input parameters for the initial setting of the case study are presented in Table 8 below.

Table 8: Summary of input parameters for the case study

Parameter[1]	$D_{X,1}$	$D_{KM,1}$	$s_{X,1}$	$s_{KM,1}$	$o_{X,1}$	$o_{KM,1}$	w^p	w_1^c	**Safety Stock**
Value	528	504	995	372	636	764	39	16	$z_\alpha \times \sqrt{PLT/_t} \times \sigma_t^D = S_i^{min}$

5.2 Cost Parameters

To complete the characteristics of the case study, the cost parameters must be identified and estimated. Inventory holding cost rate, employee salary, hiring and dismissal costs, and item variable costs must be known. These cost parameters serve as input parameters for the case study and are changed in the sensitivity analysis to expose their influence on the model.

The cost for employing one permanent employee is €30.10 per hour, while the cost of a contingent worker is €34.02 per hour. Both types of workers have a working week of 40 hours. Since only contingent workers can be hired and dismissed, hiring- and dismissing costs are only examined for contingent workers. First, a training period is incorporated in the modeling in which the operator is not productive. These costs are thus implicitly modeled. Furthermore, IRS estimates that each new worker has an average additional training period of 100 hours in its first year. This results in a training cost of €3,402. Other acquisition costs are neglected since they are on the account of the ELSA. However, a contingent worker can be easily dismissed; IRS stresses the importance of keeping workers as much employed as possible in the organization. Although no real dismissal costs are known to occur in practice, we estimate the loss of goodwill of workers with a dismissal penalty cost of €500.

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[1] In this table *x=XC60* and *KM=Kuga-Mondeo*

Lastly, the item variable costs for the XC60 roof systems are €256.85 and are €253.16 for the Kuga-Mondeo roof systems. These are simply the costs that are made by IRS to obtain the components and produce the roofs. Therefore, this is assumed to be the relevant capital that IRS has to fund, when keeping an item on shelf. The holding cost rate is estimated with the approach of Azzi, Battini, Faccio, Persona and Sgarbossa (2014) and is estimated to be 26,77% per Euro per year. The calculation of the inventory holding costs is included in Appendix J. We assume that a year contains 52 weeks and hence the holding cost rate per period is 0.51%.

5.2.1 Summary of Input Cost Parameters

In Table 9 an overview of the costs parameters, that are used for the reference model in the case study, is presented.

Table 9: Summary of input costs parameters for the case study

Parameter	C^p	C^c	C^h	C^d	C^s_{XC60}	$C^s_{Kuga-Mondeo}$
Costs per period	€1,204	€1,360.80	€3,402	€500	€1.23	€1.22

5.3 Summary of Assumptions

In this section a brief overview of all assumptions is given, to serve as a guide for the results section.

- The planning horizon is 15 periods (15 weeks), where the production schedule is updated every week (re-planning frequency). Order sizes for given weeks can change when updating the schedule. Despite the change in demand sizes, the demand is considered deterministic. Period 1 represents the week that is planned in and is thus not re-scheduled.
- Demand arrives at the beginning of the week and has to be fulfilled at the end of the week. However in practice multiple shipping days per week are planned, safety stocks, and the fact that each product is built every day, are assumed to guarantee on time delivery of orders.
- A working week contains 15 shifts; 10 strictly allocated to XC60 production and 5 to Kuga-Mondeo production. An employee is available for a full working week of 40 hours.
- The number of permanent employees is fixed and cannot be changed. Contingent capacity can be altered by hiring or dismissing workers. It is assumed that a newly hired worker always has to be trained (for one week), before becoming productive.
- Contingent workers are always employed for a whole period.
- All workers are capable of performing all tasks once they are considered trained. However, this is not true in practice; the assumption here is that a feasible allocation of available workers for a shift can always be achieved, such that al working stations are occupied.
- The contribution for each operator allocated to the system is the same, irrespective of the number of workers allocated to that station. Subsequently, it is logical that all workers have the same productivity.
- Inventory is not allowed to drop below a pre-specified minimum level and hence backorders are not allowed.

5.4 Case Study Methodology

In the case study several planning simulations are executed. Each simulation contains 10 planning cycles, where one week is skipped between re-scheduling number 5 and 6. The following procedure is strictly followed each simulation:

1. Set initial parameters.
2. Update demand data, such that it is aligned with the current planning horizon.
3. Update inventory and production schedule data, such that it is aligned with the current planning horizon.
4. Update number of permanent and contingent workers, such that it is equal to the number of workers of the previous period.
5. Run the IRS planning model.
6. Register the number of workers, the production schedule, and the inventory status of week t+1.
7. Repeat steps 2-6 until the simulation cycle is completed (after 10 periods of scheduling).

The first simulation that is executed is used as the reference model. The input parameters are set as discussed in section 5.1 and 5.2, under the assumptions of section 5.3. After the execution of this simulation run, the influence of the used parameters is tested by adjusting them and comparing the results of the planning simulation with that of the reference model. This procedure is repeated for every simulation run. Note, that the costs that are used to assess each model's performance are standardized.

The planning tool that is developed, which includes the IRS model, is included in Appendix K. The model is solved in MS Excel. The OpenSolver add-in is used for the optimization modeling. The Gurobi solver is used for calculation.

5.5 Results and Sensitivity Analysis

In this section the results of the tests with the IRS model are presented and compared. First, the reference test is presented, which resembles the current situation of IRS. Afterwards, several alternated models are presented in which each time one parameter is adjusted, compared to the reference model. The goal is to identify the influence of the parameters on the model and to compare the results to the reference test. The influence of generally two parameters is tested; inventory and labor.

5.5.1 Reference Model

The reference test is performed with the parameters set as is currently representable for IRS. The cost for a permanent worker is €30.10 per hour, while €34.02 is paid for a contingent operator. The Inventory holding costs rate is set at 26.77% per Euro per year and the training period is one week. Additionally, hiring costs are €3,402 per new employee and dismissing a worker costs €500. Lastly, safety stock is calculated each period as explained in section 5.1.4. Furthermore, all parameters, variable, sets and constraints are as mentioned in section 5.1, 5.2, and 5.3. The used capacity scenarios in all simulations are based on the scenarios shown in Table 6 and Table 7, and presented below in Table 10. Note, that it is assumed that always 5 shifts per week are available for Kuga-Mondeo production and 10 shifts for XC60 production.

Table 10: Used capacity scenarios in the case study

Week Output Kuga-Mondeo			Week Output XC60		
Capacity Scenario	**Roofs**	**FTE**	**Capacity Scenario**	**Roofs**	**FTE**
1	345	10	**1**	960	24
2	420	11	**2**	1220	26
3	560	12	**3**	1600	32
4	690	14	**4**	1760	34
5	840	16	**5**	1920	36
6	980	17	**6**	2200	38
7	1035	18	**7**	2440	44
			8	2640	48

The simulation with the reference model resulted in a total cost of **€785,135**, after calculation of ten schedules for 11 periods. As shown in Table 11, the average stock throughout the testing period is 2230 XC60 roof systems and 1008 Kuga-Mondeo roof systems. 39 permanent employees were on average accompanied by 14.8 contingent workers, while no workers had to be hired and six were dismissed during this period. The production line had a utilization of 94.14% on average, which is the difference between the maximal capacity of the scheduled scenario and the actual scheduled production quantities. Lastly, the schedule stability is presented in terms of average direction of change throughout the scheduling period (MRSE), and the average absolute change (MARSD), which is an indicator for volatility, whereas MRSE more or less delineates the trend in change. Both measures represent the change in number of workers throughout the scheduling period for a particular week. The reference model performs better than the planning performance of IRS during this period, with a total cost of respectively €785,135 and €816,700 for the IRS performance. The increase in performance is mainly due to the fact that fewer contingent workers were scheduled and fewer workers were hired and fired. Inventory was slightly higher on average however.

Table 11: Performance measures of the reference model compared to the original performance of IRS

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Reference model performance									
Average	2230	1008	39	14.8	0	6	95.14%	4.3	10.0
Cost	€ 30,167	€ 13,641	€ 516,516	€ 221,810	€ 0	€ 3,000			
IRS original performance									
Average	1361	629	39	16	9	9	95,16%	1	6
Cost	€ 18.411	€ 8.515	€ 516.516	€ 238.140	€ 30.618	€ 4.500			

For the other tests, the reference model is used as baseline measure, and one parameter per test is adjusted to assess the influence of the parameter. The parameters that are chosen for the tests are based on practical assumptions and practical application of the concepts. However cost parameters might be adjusted to examine the change in the behavior of the IRS model, the costs outputs are all standardized, such that realistic comparisons can be made.

5.5.2 Influence of Inventory

Inventory is currently the main driver for production planning at IRS. Having inventory is considered costly and therefore inventory levels are kept as low as possible. On the other hand safety stock is used to cope with uncertainty in the supply chain, and might prevent for costs caused by unexpected events. Inventory has two factors that influence the behavior of the IRS model; (1) the holding cost rate that stresses the weight that inventory plays while optimizing total costs, and (2) the height of the safety stock, which affects the average level of inventory.

5.5.2.1 Inventory Holding Cost is 15%

First, the inventory holding cost rate is reduced to 15%. This value is chosen since it is currently estimated as the inventory holding costs rate, by IRS's Logistics manager. Choosing a lower cost rate implies that inventory is considered less expensive and thus, theoretically, might be considered less important when optimizing the production planning. The results are given in Table 12. The total costs for the testing period for this model are **€807,345**, which is worse than the reference model (€785,135). This is caused by a higher average inventory and a higher number of contingent workers that are hired on average. Also, hiring costs were higher in this simulation. The explanation for the higher inventory costs is straightforward; since the holding costs rate is lower, the importance to reduce inventory is smaller. On the other hand the explanation for the higher number of contingent employees is caused by the relatively greater weight that is given to labor costs. This results in a planning model that tries to reduce the workforce size whenever possible, resulting in the hiring of workers when demand forecasts change.

Table 12: Performance measures of the model with 15% holding costs

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	2500	1283	39	15.5	2	3	96.70%	4.2	6.6
Cost	€ 33,823	€ 17,365	€ 516,516	€ 231,336	€ 6,804	€ 1.500			

5.5.2.2 Safety Stock is 1.6 Days Safety Lead Time

The next model assumes the safety stock level that is currently used by IRS; 1.6 days of demand as safety lead time. This is lower than the calculated safety stock of the reference model, as is presented in Table 13. Note, that also the average safety stock levels for the next model (section 5.5.2.3) are included.

Table 13: Average safety stock level for different safety stock policies

	Reference model SS	1,6 days safety lead time	SS for demand and due date variance
XC60	863,5	577,6	1861,8
Kuga-Mondeo	478,1	264,4	1038,2

Lowering the safety stock level involves accepting a greater risk on stock-outs and related penalty costs. The performance of this model is summarized in Table 14. Total costs of the system for this model are **€754,006**, which is less than the costs of the reference model (€785,135). It is noteworthy, that stock levels do not decrease below the safety stock boundary of the reference model on average. Hence, it might be concluded that inventory costs are decreased while avoiding increased risks. Also, contingent labor costs are lower, which is due to the fact that the lower boundary on inventory is less likely to be violated, since it is lower.

Table 14: Performance measures of the model with minimally 1.6 day safety lead time

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	1386	1399	39	13.2	0	5	96.39%	5.2	9.5
Cost	€ 18,749	€ 18,925	€ 516,516	€ 197,316	€ 0	€ 2,500			

5.5.2.3 Safety Stock Accounts for Variance in Order Due Date

The last inventory parameter change is the increase of the safety stock level, which is most likely to increase average stock levels for this model. Another safety stock policy is proposed that includes the variability of change in order due dates. Since, customers are allowed to expedite orders with two days the following calculation is used (elaborated in Appendix I):

$$Safety\ Stock = \left(z_\alpha \times \sqrt{{}^{PLT}/_{t}} \times \sigma_t^D\right) + (z_\alpha \times \sigma^{PLT} \times \mu_t^D)$$

The deviation of the due dates within the planning lead time σ^{PLT} is set on 2 days (0.4 periods) to cover for the allowed contractual variances. This is multiplied by the average demand during one period μ_t^D, such that it covers the average demand in 2 days. The safety stock is calculated before every scheduling attempt and is based on the demand within the planning horizon, as is the case in the reference model. Total costs for this model are higher than the reference model; **€805,867** compared to €785,135 of the reference model. Results are depicted in Table 15. The decrease in performance is most likely due to the fact that the inventory costs are higher compared to the reference model, which is intuitive since the lower boundary on inventory is higher.

Table 15: Performance measures of the model with safety stock that accounts for variance in due dates

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	3418	1855	39	14.4	0	6	95.40%	5.0	7.7
Cost	€ 46,248	€ 25,096	€ 516,516	€ 215,006	€ 0	€ 3,000			

5.5.3 Influence of Labor

Besides inventory, the cost of labor is another driver for the IRS model. Labor costs are even multiple times bigger than inventory costs, but might be harder to control, since one can argue that labor is needed to produce. In this model labor has three main customizable characteristics; length of the training period, the ratio between hiring- and dismissal costs, and the ratio between permanent and contingent employees. The wages of the workers are assumed to be fixed.

5.5.3.1 Training Period is Three Weeks

First, the length of the training period is increased to three weeks and the cost for hiring a worker is reduced to €1000. This is to reduce the training costs that are incorporated in the hiring costs by two weeks of salary. The €1000 of hiring costs is estimated, since some overhead costs are assumed to remain and always some additional training remains required. The training period of three weeks is chosen, since IRS management estimates that this is a reasonable training time for an operator to become widely employable (cross-trained). The results for this model are included in Table 16 and total costs for this model are **€769,505**; lower than the reference model (€785,135).

Table 16: Performance measures of the model that includes a three week training period

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	1500	1197	39	14.4	0	3	95.16%	4.1	15.1
Cost	€ 20,291	€ 16,192	€ 516,516	€ 215,006	€ 0	€ 1,500			

Holding costs are slightly reduced compared to the reference model, as well as the costs of contingent capacity and the costs of dismissal. This is most likely caused by the fact that a longer training period makes the model less flexible and thus less affected by demand volatility.

5.5.3.2 Hiring Costs are Equal to Dismissal Costs

Another setting is that hiring costs and dismissal costs are equal (both €1,951). This puts some more emphasis on the fact that dismissing workers might not be favorable in terms of social economical responsibility, for example. The total costs for this model are **€803,098**, which is a performance decrease compared to the total costs (€785,135) of the reference model. The performance measures are presented in Table 17. The increase in costs is probably caused by the relatively high hiring and dismissal costs. This is likely to prevent the model to dismiss excess capacity when it could and consequently leading to higher stock levels and an increased workforce size.

Table 17: Performance measures of the model that has equal hiring and dismissal costs

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	2559	1313	39	15.5	0	3	96.83%	3.2	7.9
Cost	€ 34,618	€ 17,768	€ 516,516	€ 232,697	€ 0	€ 1,500			

5.5.3.3 Hiring Costs and Dismissal Costs are Reversed

This model considers the costs for hiring and dismissal reversed (€500 for hiring a worker and €3,402 for dismissing one). It is argued that by dismissing an operator valuable knowledge is lost to IRS, and that this might be considered more important than training a new worker. A secondary benefit might be that the IRS model is less inclined to dismiss workers at the end of the planning horizon, due to the natural behavior of the used optimization algorithm. Consequently, inventory levels and workforce levels might be more stable. The total costs for this model are **€761,316**, which is significantly better than the total costs (€785,135) of the reference model. The performance of this model can be retrieved from Table 18. The performance increase of the model is mainly due to the decrease in inventory and the decrease in contingent capacity. This is possibly due to the fact that the model can dismiss workers early in the planning horizon, since acquiring new workers is relatively cheap.

Table 18: Performance measures of the model that has high dismissal- and low hiring costs

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	1250	1209	39	13.6	1	8	96.43%	3.9	9.9
Cost	€ 16,915	€ 16,363	€ 516,516	€ 204,120	€ 3,402	€ 4,000			

5.5.3.4 Optimal Ratio of Permanent and Contingent Employees

The last model uses an optimal ratio of permanent and contingent workers. The optimum number of permanent workers is estimated by means of one year of monthly customer forecasts. The IRS model is used, in which periods were changed to months, instead of weeks, and the planning horizon was 12 periods (one year). No re-scheduling effort took place, since no additional data was available. All other parameters were left unchanged, except that they were scaled to months instead of weeks. Details of the calculation are presented in Appendix L.

The optimal number of permanent employees was estimated to be 50. This implies that 11 contingent employees could be offered a permanent contract, against lower costs for IRS, compared to the current situation. This results in a total costs during the testing period of **€746,153**, which is better than the reference model (€785,135). This results in the best performing model; average stock, schedule volatility, and labor costs are all relatively low, as can be concluded from Table 19. This is mostly due to the decreased labor costs, since permanent workers are cheaper than contingent employees. The increased schedule stability is due to the fact that permanent workers cannot be dismissed, and consequently reduces the flexibility of the model, to respond to demand volatility.

Table 19: Performance measures of the model with an optimal number of permanent employees

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	1380	691	50	3.2	2	3	94.92%	-0.5	5.2
Cost	€ 18,671	€ 9,349	€ 662,200	€ 47,628	€ 6,804	€ 1,500			

5.5.4 Reference Model with Frozen Period Incorporated

Besides adapting labor and inventory parameters, the characteristics of the planning model itself can be altered. One of the most effective methods to reduce costs, according to Hopp and Spearman (2000), are the incorporation of a frozen period in the master production schedule. This is a period in the beginning of the planning horizon in which changes on the schedule are not allowed. IRS uses four weeks of frozen period in theory, but this policy is more often neglected than that is committed to. The advantage of honoring the frozen period is that always the first few upcoming weeks are without changes, which eases management's life. Therefore, the reference model was adapted, such that it includes four weeks of frozen period. This resulted in a total cost of **€795,785**, which is slightly more costly than the reference model (€785,135) (see Table 20). There can be concluded that the predictability that the frozen period offers, comes at a price. The decrease in performance is mostly caused by higher inventory levels, which is caused by decreases in demand volumes in the first weeks of the planning horizon. Note, that schedule stability after the frozen period, performs worse than the reference model. This implies that when the model has a longer planning horizon, in which it can schedule, the model becomes more stable.

Table 20: Performance measures of the reference model with 4 weeks frozen period incorporated

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	3254	1274	39	14.4	0	6	95.24%	5.5	8.7
Cost	€ 44,029	€ 17,234	€ 516,516	€ 215,006	€ 0	€ 3,000			

5.5.5 Model with Optimal Settings Combined

Lastly, a model is built in which all parameters settings that performed better than the reference model are combined. This means that safety stock is set on 1.6 days of safety lead time, hiring- and dismissal costs are reversed, the training period for a new worker is 3 weeks, and that the optimum number of 50 permanent employees is included in the system. The assumption behind this is that the combination of good parameter settings, will result in better performance of the IRS planning model. However, this is not certain, since the interaction between certain parameters could always influence the model negatively. Once again all costs are standardized.

The results of this "optimal" model are shown in Table 21. The total costs for this model during the testing period are **€738,066**, which is the best performance of all models, including the reference model (€785,135). Utilization is rather low compared to other models, as well as the schedule stability measures (implying a stable schedule). Also, inventory levels are reduced compared to other models. Solely the cost of hiring contingent workers is higher compared to the reference model, but this is outweighed by the increases in labor- and inventory cost performance.

Table 21: Performance measures of the model with all optimal parameter settings combined

	XC60 stock	Kuga-Mondeo Stock	# Permanent Workers	# Contingent workers	# of hired	# of dismissed	Utilization	MRSE	MARSD
Average	966	648	50	2.7	3	6	92.88%	0.2	2.4
Cost	€ 13,074	€ 8,761	€ 662,200	€ 40,824	€ 10,206	€ 3,000			

5.6 Conclusion of Results

When comparing the performance of all models, it becomes clear that the quality and setting of the input parameters has a significant influence on the quality of the planning model's output, as can be retrieved from Table 22. Note, that all costs are standardized, including the original costs of the IRS planning. The costs used in the analyses are standardized lower bound costs, since this would provide the most reliable evaluation. Over-time costs and emergency shipment costs are not included in these analyses. Furthermore, the used capacity scenarios are based on empirical data, but remain an approximation of the true behavior of the production system, when adding a worker to the system. Nonetheless, these scenarios should provide a sound insight in the methods of planning, and in the practical use and the importance of the capacity scenarios.

Table 22: Comparison of the performance of all tested planning models

Model	Inventory Costs	Labor Costs	Acquisition Costs	Utilization	MRSE	MARSD	Total Costs	Reference Model Performance Increase	IRS Performance Increase
IRS performance	€ 26,926	€ 754,656	€ 35,118	95.16%	0.7	5.8	**€ 816,700**	-4.0%	0.0%
Reference model	€ 43,808	€ 738,326	€ 3,000	95.14%	4.3	10.0	**€ 785,134**	0.0%	3.9%
15% holding costs	€ 51,188	€ 747,852	€ 8,304	96.70%	4.2	6.6	**€ 807,344**	-2.8%	1.1%
1.6 days SS	€ 37,674	€ 713,832	€ 2,500	96.39%	5.2	9.5	**€ 754,006**	4.0%	7.7%
Due date variability SS	€ 71,344	€ 731,522	€ 3,000	95.40%	5.0	7.7	**€ 805,867**	-2.6%	1.3%
3 week training period	€ 36,483	€ 731,522	€ 1,500	95.16%	4.1	15.1	**€ 769,505**	2.0%	5.8%
Hiring- equals dismissing costs	€ 52,386	€ 749,213	€ 1,500	96.83%	3.2	7.9	**€ 803,098**	-2.3%	1.7%
Reversed hiring and dismissal costs	€ 33,278	€ 720,636	€ 7,402	96.43%	3.9	9.9	**€ 761,316**	3.0%	6.8%
Optimal number permanent workers	€ 28,021	€ 709,828	€ 8,304	94.92%	-0.5	5.2	**€ 746,153**	5.0%	8.6%
Frozen period	€ 61,263	€ 731,522	€ 3,000	95.24%	5.5	8.7	**€ 795,785**	-1.4%	2.6%
Optimal model	€ 21,836	€ 703,024	€ 13,206	92.88%	0.2	2.4	**€ 738,066**	6.0%	9.6%

First, the chosen safety stock policy has a great influence on the average number of items that are kept on shelf; using a policy that allowed for less safety stock, resulted in significantly decreased inventory levels. Likewise, the height of the inventory holding costs rate had an influence on the performance of the IRS model. When reducing holding costs rate, less emphasis was put on reducing inventory, and consequently resulted in worse system performance. Furthermore, the modeling of a longer training period and change in the ratio between hiring and dismissal of a worker had clear influence on the planning model's behavior. Especially, reversing training and dismissal costs contributed greatly to the model's performance. The effect of increasing the training period was positive, but less profitable. On the other hand, equaling the costs of hiring and dismissal had a negative impact on cost performance. The most profitable parameter change was the optimization of the ratio between contingent and permanent employees in the production system; this impacted the system costs most positively. Lastly, incorporating a frozen period in the planning period was slightly more costly than the reference model.

When regarding the more intangible performance measures, the different models seem to have hardly any influence on system utilization. Only, the model that combined the different optimal settings seems able to reduce the utilization. This makes the system more capable to cope with unexpected problems. Also, the schedule stability, measured in MRSE and MARSD, seems relatively uninfluenced by the system. Re-scheduling fluctuation seems randomly influenced by the different parameter settings. The schedule stability of the original planning of IRS performs better than that of any of the IRS models. Only the optimal model has a lower MRSE and MARSD during the testing period. Note, that these measures are merely indicators and that their value should not be overestimated.

In conclusion, the setting of the input parameters of the model can be considered very important. We were able to improve the internal performance of the IRS planning model by 6%, by adjusting some parameters. This could possibly be further optimized by analyzing the parameters more in-depth. Compared to the actual situation of IRS, savings up to approximately 9.6% can be achieved by the IRS planning model, for this production line. This is an estimated saving of €371,724 per year.

6 Implementation Plan

In this study an aggregate capacity planning tool is developed for industrial environments in which organizations like IRS operate. The goal of this tool was to optimize the production capacity planning for the intermediate-term. In order to fully benefit from the potential advantages that the planning tool might provide, it should be implemented with care. In this section an overview is given on the proposed implementation plan.

The first and foremost step in the implementation of the planning tool, is to train the employees at the planning department, who have to work with the planning tool. However the calculation of an optimal production plan is automated in the tool; knowledge about the functioning of the tool, the assumptions behind the tool, and the parameters that influence the tool's behavior, is crucial for a good and credible production schedule. Despite the fact that the tool finds the best feasible production schedule, deviations might occur that the tool cannot handle. Think of data errors, problems that decrease production capacity for a period, or unreasonable or unexpected demand patterns. In case of such events, it is advisable to let a human intervene in the production plan and adjust it into a realistic plan, given the mentioned events. Therefore, the employees that work with the tool need to be trained to be able to cope with any unexpected events.

After training, the production schedulers should be able to copy the tool and transfer it to the other production lines of IRS. The tool should be adjusted for each production line, since each production line has its own characteristics, constraints, and assumptions. The roll-out of the tool to other production lines makes it more beneficial for IRS, since it accelerates the production planning process, and consequently might increase response time to planning related problems. With the roll-out of the planning tool, the tool could also be improved in functionality, which is explained in the recommendations of this study in section 7.3.

Furthermore, it is advisable for a scheduler, or for management, to keep track of the trends that influence the planning; demand should be monitored, parameters and capacity scenarios should be kept up-to-date, and workforce composition could be reconsidered. This way the accuracy and the output of the tool remains warranted. The most important task, for a successful implementation, is the estimation of proper capacity scenarios. The scenarios used in this research are estimates based on the assumption that the relation between the output of a working station and the number of workers at a production station is linear. As mentioned, in practice this is most likely not the case. Therefore, it would be a major contribution to the quality of the output of the planning tool, when the capacity scenarios would be a better representation of the actual situation. We believe that it is better to have a few, but accurate, capacity scenarios, than many erroneous scenarios.

Additionally, some parameters should be kept up-to-date to secure the accuracy of the planning tool. The wages of both permanent $\boldsymbol{C^p}$ and contingent $\boldsymbol{C^c}$ workers change over time. An annual increase of salary is customary, and hence it is advisable to update these parameters each year. Especially, a change in ratio between the two types of workers might have a great effect on the behavior of the planning tool. Consequently, unnecessary costs can be prevented by timely adjustment of parameters.

The same goes for the holding cost rate $\boldsymbol{s_{i,t}}$. It is sensible to keep it as accurate is possible, such that the planning tool values inventory correctly, and does not over- or underestimate its costs. It is easiest to update it once per year, when financial data is analyzed and/or issued in the annual report, for example.

Subsequently, the hiring $\boldsymbol{C^h}$ and dismissal $\boldsymbol{C^d}$ costs could be better monitored than currently done. This provides better input data for the planning tool, but might also give better insights in the flexibility of the production system, in terms of ability to change capacity and to change workforce size. When parameters resemble the true costs that are made, the tool might give manager insights in capacity decisions and whether a level production should be pursued or a more flexible production policy should be realized.

Also the length of the planning horizon and the re-planning frequency could be taken under consideration. However, not all customers provide demand forecasts that reach further than 15 weeks currently; it is most likely beneficial to increasing the planning horizon. The IRS model might be able to more accurately level the production capacity between periods, when it is able to calculate a planning over more periods. Additionally, the re-planning frequency might be reconsidered. The tool is designed to calculate an optimal production plan for the whole planning horizon. The effect of re-scheduling is not taken into account when performing the re-scheduling activity. Hence, it is arguable that the production plan would perform better when the re-planning frequency is decreased. Consequently, the safety stock policy should be adjusted for the change in re-planning frequency by increasing $\boldsymbol{PLT}$.

Furthermore, it might be beneficial to restrict the utilization of the scheduled available production capacity, in order to cope with production uncertainty. As highlighted in section 3.1.1.3, the production system loses capacity due to technical downtime and quality rejects of products. We estimated that downtime and rejects consume approximately 13% of the production capacity on average. When the planned utilization of the production system is able to cope with this the uncertain capacity losses, over-time working- and emergency shipment costs might be greatly reduced. The idea to plan up to a maximum of 80% to 90% of the maximum capacity is generally accepted in practice, to be able to cope with uncertainty and prevent for ever increasing queues (Hopp & Spearman, 2000).

In conclusion, the planning tool is designed to be able to cope with growth or decline of demand. Safety stock levels adapt to these trends, regardless of the safety stock policy chosen. Also, costs are ever optimized given the demand patterns that are faced, given al inputs and constraints. The optimality of the calculated production plan could be improved by extending the scope of the tool. As long as the production process does not change, the tool should function properly. Whenever changes in the production process occur, the influence on the production planning should be evaluated and the planning tool should be adjusted when necessary.

Lastly, as mentioned in literature (De Sousa et al., 2014; Kjellsdotter-Ivert & Jonsson, 2010); the benefits of integrating the production planning in the organization’s ERP system improves the quality of the planning and gives more possibilities to monitor, evaluate and adjust the production plan. Therefore, it is advisable to investigate the possibility to integrate the production planning in the ERP system of IRS. It might improve the quality of the production plan and it gives the possibility to schedule on different hierarchical levels, such as short term order scheduling, intermediate term-master production scheduling, and long-term capacity planning.

7 Conclusion, Discussion, and Recommendations

In the previous sections the research questions and its sub-questions are answered. They are built around the research assignment; *"Develop a production control methodology for a single, multi product flow line production system with discrete dynamically adjustable production capacity per working station, constrained by limited production capacity, high backordering costs, and a demand fulfillment requirement"*. The main research question, supporting the research assignment, is the following:

How can the production planning problem of IRS be improved/optimized, considering fluctuating customer demand and resource capacity constraints on a multi-product assembly line in a make-to-order production environment?

The production planning process at IRS can be improved by means of the IRS model, which is developed in chapter 4, integrated in the provided production planning tool. The tool calculates an optimized production plan, given the demand faced at the time of planning, and copes with the fluctuating demand by adjusting the safety stock each time new demand patterns are seen. The automated execution of the planning process results, besides in an optimized planning, also in a more time efficient planning process. Hence, the benefits are twofold; planning time is reduced, and the planning quality is improved. The total benefits can add up to cost savings of 9.6% annually.

In this section the most important conclusions of the research are highlighted in section 7.1 and 7.2. In section 7.3 practical recommendations are made to IRS, while in section 7.4 the theoretical contribution is highlighted. Lastly, the limitations of this research are illustrated and future research directions are given, in section 7.5.

7.1 Conclusions from Analysis

In the analysis phase an overview of the IRS production environment is given. The main characteristic of the IRS production system that is revealed is the option to increase capacity per production station and thus the option to change the bottleneck station in the system. Furthermore, it is demonstrated that the demand is distributed normally, and that it changes for any given week when updating the demand forecasts (volatility). The demand volatility is also proven to be distributed normally. Likewise, the re-planning stability is measured. However re-planning stability is less volatile than the demand stability, the production schedule stability could be improved. Lastly, it is concluded that many seemingly unnecessary costs are made, which implies the need for improvement.

Two models are developed in the method development phase; that aimed at optimizing total system costs over the planning horizon, which is in principal a combination of labor related costs and inventory costs. The first developed model, the BCPM, is designed such that it explicitly incorporates the capacity planning for each working station in production line. The idea behind this is that only a few combinations of allocated workers to each production station (scenarios) are efficient, since the bottleneck of the system determines the systems output. On this assumption the IRS model is built. It makes use of capacity scenarios that can be retrieved from the BCPM. However, we are unable to estimate the contribution functions of allocated workers for each station $\boldsymbol{P_{i,j}(a_{i,j,t})}$. Hence, efficient capacity scenarios are developed based on the assumption that each worker contributes a given output to a production station. These capacity scenarios are included in the IRS model, used in the case study. However the IRS model is a relaxation of the BCPM, it is more applicable in practice, since it demands less computational effort and relates better to the current needs and practices.

In the case study phase the developed IRS model was tested against the current performance of the IRS production system. The IRS model demonstrates to provide better production schedules that are less costly. Furthermore, the model's parameters are reviewed, showing that adjusting the parameters of the model could further improve the optimality of the output of the model; the production plan. The influence of the parameters is discussed below.

7.2 Influence of Parameters

To test the influence of the planning parameters 10 different models are tested in section 5.5. It is concluded here that choosing for low safety stock levels, and putting greater weights on inventory holding costs increased the models performance. It is worth noting that decreasing safety stock levels, increases the risk on stock-outs and thus on emergency shipment costs and over-time costs. Those are inherently higher than all regular costs included in the production system. Furthermore, adjusting the parameters of the model does not necessarily change the costs when regarding standardized costs. The systems total costs might theoretically be improved when decreasing the holding cost rate, since keeping inventory in stock is less costly. However, in practice the price paid for holding inventory will not change, even when the exact holding cost rate is unknown.

Furthermore, the influence of hiring- and dismissal costs is tested, as well as the re-modeling of those costs by increasing the training period. It is shown that the IRS model behaves more optimal when more emphasis is put on dismissal costs rather than on hiring costs. Also, increasing the training period to three weeks and reducing hiring costs accordingly resulted in better system performance. However improvements are easily made in the model's performance, more research is needed to optimize the setting of the parameters. In this research a limited number of possible parameter settings were tested, due to time limitations. For each environment in which the model is used a comprehensive analysis should be made on the setting of the parameters to ensure optimal use of the planning tool.

Lastly, the incorporation of a frozen period in the model is tested. However it is generally considered to increase schedule stability, the opposite is found in this study. This might be due to the fact that the first four weeks in the planning horizon are unchanged, and consequently the demand volatility has to be coped with in a reduced period of time. This might cause greater changes in the unfrozen part of the schedule. Therefore, a frozen period might be more useful in a model with a longer planning horizon. Also, the benefits that a frozen period incorporates, such as the reliability of the production schedule in the first few weeks, are not measured in this research. When the incorporation of a frozen period prevents for over-time production and/or emergency shipments, it might be more beneficial than shown in this research.

7.3 Practical Recommendations

Based on the findings given above, and in previous sections of the thesis, some practical recommendations are made to IRS. In order to make the planning tool more useful, a roll-out of the planning methodology to other production lines is advisable. Therefore, it is assumed that the intention is to implement the planning tool, throughout the whole organization, in the recommendations that are given below:

- The production planning tool is most efficient when it is implemented for all production lines at IRS in the Venray plant, and most favorably in all factories. Consequently, the work of production planners is consistent, and the most time is saved on the planning process itself.
- It might be beneficial to reduce the re-planning frequency. The planning tool is likely to perform better under a decreased re-planning frequency, resulting in fewer changes in the production plan, and a more efficient use of capacity.
- The tool should be used to estimate the ideal ratio between permanent and contingent workers once every period (for example each year). On production lines with a volatile average demand

a greater number of contingent employees is, most likely, more desirable than on a production line with a rather stable average, such as the XC60-Kuga-Mondeo assembly line.

- Production planners should be responsible for the evaluation of the performance of the planning tool. Also, unexpected events that occur and might impact the IRS production system should be manually updated to the planning tool by the production planners. A bankruptcy of a customer or a crash on the stock market (that causes an economic recession) are such events, for example.
- Production planners should focus on the correct estimation and evaluation of parameters and capacity scenarios, rather than on creating an MPS. This way the quality of the models is warranted when the production environment changes over time.
- It is advisable to focus on the terms that influence uncertainty when negotiating new contracts with customers, such that demand volatility decreases. This is likely to reduce the total costs of the production system and reduces the impact of re-scheduling on the production plan.
- Furthermore, the model could be extended by incorporating the possibility to explicitly model the number of shifts that is worked each week. In the IRS model, the number of shifts can be implicitly model by creating different scenarios, with different shift systems. This could be extended by making the model able to decide on the number of shifts that should be worked every week, and let it decide on the allocation of the shifts over the different products.
- Likewise, the model could be extended by incorporating all production lines of one plant into one model. This makes it possible to exchange operators between assembly lines and consequently the number of dismissals (and hiring's) of employees can be reduced. Additionally, the ratio between permanent and contingent employees might be improved, since fluctuations in demand can be coped with within the organization, instead of hiring contingent capacity from the ELSA.
- Additionally, it is advisable to monitor the total loss of output (quality rejects and technical downtime) for each assembly line and adjust the maximum utilization accordingly. As is analyzed in section 3.1.1.3, the average loss of capacity of the XC60-Kuga-Mondeo production line is estimated to be 13%. Therefore, it is advisable to restrict the maximum allocated number of planned orders, such that no over-utilization occurs.
- Lastly, the models proposed in this research could be integrated in IRS's ERP system. This would greatly enhance the possibility to response to unexpected events in a timely manner, when necessary. Also, a better connection and integration to the shop floor, the MRP system, financial department, and other related departments and stakeholders could be made. Furthermore, the daily detailed order scheduling could be incorporated in the MPS planning, resulting in a more efficient production schedule.

7.4 Theoretical Contribution

This research contributes to literature by providing a MINLP model that assumes the possibility to adjust capacity per production station, by allocating a number of operators to that station, each period. Furthermore, the model includes inventory and backorders, the costs of hiring and dismissing employees, and distinguishes permanent and contingent workers. This is, to the best of our knowledge, a unique model in literature that (partially) extends the model of Sillekens et al. (2011). Furthermore, insights are provided on the behavior of the IRS planning model under different parameter settings. It is shown that a planning model might behave better in practice when the used parameter settings deviate from the reality, or are set under another interpretation of this reality. Think of the example of the modeling of hiring- and dismissal costs in this case.

7.5 Limitations and Future Research Directions

However this research certainly provides valuable practical and academic insights, it also is restricted by some practical boundaries and limitations. Those are described below:

- The BCPM is developed but not tested due to practical feasibility. The computational power needed to optimize the complex non-linear model was not available, and thus the model's performance is not tested.
- It is assumed that there exists homogeneity among all workers. It might be argued that in practice the output per operator differs, and consequently the output per shift might differ.
- This research focuses on only one production line at IRS, while their production system contains several assembly lines per factory. Planning for a whole factory instead of scheduling per production line independently is likely to be beneficial. Consequently, operator availability can be scheduled for the whole organization and hiring and dismissal of employees can be coped with internally first, before forwarding a request to the ELSA.
- For this research, it is assumed that the allocation of shifts between the two product groups on the production line is fixed. This is due to limited capacity of certain pre-assembly processes. Nonetheless, it can be valuable to enable the model to decide upon the allocation of shifts towards products. This increases the flexibility of the production system.
- Furthermore, the relation between the aggregate level MPS and the detailed level order scheduling could be incorporated in the planning tool. This enhances the feasibility of the production schedule, in practice.
- Also, the number of shifts that are available each week could be incorporated as a decision variable in the model. Note, that it becomes necessary to model the costs of changing the shift system, such that it would not change once every week.
- The capacity scenarios used in the analysis are linear approximations of the real output functions. Therefore, the results of the model are not strictly accurate. Consequently, it is important to investigate the behavior of the working stations in the system more extensively, to obtain better results.
- Another assumption of this research is that a new worker is not productive for its entire training period and that it is 100% productive after completion of its training. It can be argued that this might not be the case in practice; however, IRS uses this assumption as well.
- The data sets in this study could have been bigger, but many data was lost due to a change of the ERP system in March 2014. This might have influenced the results of the analysis, but this remains unclear.
- The simulation period used in the case study section might be too short to provide stable results. This was due to the processing time of the simulation runs and we preferred the option to do several runs over one long run. Therefore, future research could focus the behavior of the planning model over a longer period.
- Lastly, it could be possible to extend the model by allowing for scheduling of over-time, or by incorporating the option of outsourcing certain production tasks, to increase capacity. These are options that might be especially interesting for other organizations or for production lines that are producing at maximum capacity.

List of Abbreviations

APS	Advanced Planning and Scheduling
BCPM	Bottleneck Capacity Planning Model
CMAD	Cumulative Mean Absolute Deviation
CMARSD	Cumulative Mean Absolute Re-Scheduling Deviation
CMFE	Cumulative Mean Forecasting Error
CMRSE	Cumulative Mean Re-Scheduling Error
ELSA	External Labor Supply Agency
EOL	End-of-Line (station)
ERP	Enterprise Resource Planning
FTE	Full-Time Equivalent
HPP	Hierarchical Production Planning
IRS	Inalfa Roof Systems (Group)
KS	Kolomogorov-Smirnov
MAD	Mean Absolute Deviation
MARSD	Mean Absolute Re-Scheduling Deviation
MFE	Mean Forecating Error
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MPS	Master Production Schedule
MRP	Materials Requirements Planning
MRSE	Mean Re-Scheduling Error
MSS	Master Surgery Schedule
MTO	Make-to-Order
MTS	Make-to-Stock
OEM	Original Equipement Manufacturer
PLT	Planning Lead Time
S.D.	Standard Deviation
SS	Safety Stock
SW	Shapiro-Wilk
TPS	Toyota Production System
WIP	Work-in-Progress

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Bibliography

Alp, O., & Tan, T. (2008). Tactical capacity management under capacity flexibility. *IIE Transactions*, *40*(1), 221–237.

Azzi, A., Battini, D., Faccio, M., Persona, A., & Sgarbossa, F. (2014). Inventory holding costs measurement: a multi-case study. *International Journal of Logistics Management*, *25*(1), 109–132.

Bakens, S. (2015). *An overview on different aspects of production planning; particularly focusing on MPS* (Literature Review). Eindhoven University of Technology, Eindhoven.

Barlatt, A., Cohn, A., Fradkin, Y., Gusikhin, O., & Morford, C. (2009). Using composite variable modeling to achieve realism and tractability in production planning: an example from automotive stamping. *IIE Transactions*, *41*(1), 421–436.

Beliën, J., Demeulemeester, E., & Cardoen, B. (2009). A decision support system for cyclic master surgery scheduling with multiple objectives. *Journal of Scheduling*, *12*(1), 147–161.

Bertrand, J. W. M., Wortmann, J. C., & Wijngaard, J. (1998). *Productie-beheersing en materials management* (2nd ed.). Houten: Wolters Noordhoff.

Boysen, N., Fliedner, M., & Scholl, A. (2009). Production planning of mixed-model assembly lines: overview and extensions. *Production Planning & Control*, *20*(5), 455–471.

Broens, R. (2013). KIVI NIRIA. Retrieved May 18, 2015, from https://www.kiviniria.net/tr?transaction=KIVI_ACT006&PARAM1=3400

Buyukkaramikli, N. C., Bertrand, J. W. M., & Van Ooijen, H. P. G. (2013). Flexble hiring in a make to order system with parallel processing units. *Annals of Operations Research*, *209*(1), 159–178.

Cardoen, B., Demeulemeester, E., & Beliën, J. (2010). Operating room planning and scheduling: a literature review. *European Journal of Operational Research*, *203*(1), 921–932.

Chiang, C. Y. (2011). *An econometric investigation of the bullwhip effect - The influence of demand and supply in the automobile industry* (Dissertation). University of Buffalo, Bufallo.

Deleersnyder, J. L., Hodgson, T. J., King, R. E., O'Grady, P. J., & Savva, A. (1992). Integrating Kanban type pull systems and MRP type push systems: insights from a Markovian model. *IIE Transactions*, *24*(3), 43–56.

De Sousa, T. B., Camparotti, C. E. S., Guerrini, F. M., Da Silva, A. L., & Júnior, W. A. (2014). An overview of the advanced planning and scheduling systems. *Independent Journal of Management & Production*, *5*(4), 1032–1049.

Dhingra, A., & Chandna, P. (2010). Multi-objective flow shop scheduling using hybrid simulated annealing. *Measuring Business Excellence*, *14*(3), 30–41.

Dörmer, J., Günther, H. O., & Gujjula, R. (2015). Master production scheduling and sequencing at mixed-model assembly lines in the automotive industry. *Flexible Service Manufacturing Journal*, *27*(1), 1–29.

Easton, F. (2014). Service completion estimates for cross-trained workforce schedules under uncertain attendance and demand. *Production and Operations Management*, *23*(4), 660–675.

Ernst & Young. (2013). *Eight mega trends shaping the global light vehicle industry* (pp. 1–4). New York: Ernst & Young LLP.

Feng, K., Rao, U. S., & Raturi, A. (2011). Setting planned orders in master production scheduling under demand uncertainty. *International Journal of Production Research*, *49*(13), 4007–4025.

Framinan, J. M., & Ruiz, R. (2010). Architecture of manufacturing scheduling systems: literature review and an integrated proposal. *European Journal of Operational Research*, *205*(1), 237–246.

Gahm, C., Dünnwald, B., & Sahamie, R. (2014). A multi-criteria master production scheduling approach for special purpose machinery. *International Journal of Production Economics*, *149*(1), 89–101.

García-Sabater, J. P., Maheut, J., & García-Sabater, J. J. (2012). A two-stage sequential planning scheme for integrated operations planning and scheduling system using MILP: the case of an engine assembler. *Flexible Service Manufacturing Journal*, *24*(1), 171–209.

Heneric, O., Licht, G., & Sofka, W. (2006). *Europe's automotive industry on the move: competitiveness in a changing world* (Vol. 32). Heidelberg: Springer Science & Business Media.

Henig, C., Rieck, J., & Zimmermann, J. (2014). Integrated production and staff planning for hetrogeneous, parallel assembly lines: an application in the automotive industry. *International Journal of Production Research*, *52*(13), 3966–3985.

Herron, C., & Hicks, C. (2008). The transfer of selected lean manufacturing techniques from Japanese automotive manufacturing into general manufacturing (UK) through change agents. *Robotics & Computer-Integrated Manufacturing*, *24*(4), 524–531.

Hiel, P. (2015, April 16). Introduction in operations department at IRS Venray.

Holweg, M., Davies, P., & Podpolny, D. (2009). *The competitive status of the UK automotive industry*. Buckingham: PICSIE Books.

Holweg, M., & Pil, F. K. (2001). Successful build-to-order strategies start with the customer. *Sloan Management Review*, *43*(1), 74–83.

Hopp, W. J., & Spearman, M. L. (2000). *Factory physics: fundamentals of manufacturing management* (2nd ed.). New York: Irwin/McGray-Hill.

IBM. (2009). *The smarter supply chain of the future: global chief supply chain officer study* (pp. 1–24). Somers: IBM Global Services.

Inalfa Roof Systems. (2013). Inalfa Roof Systems Group. Retrieved May 18, 2015, from http://www.inalfa-roofsystems.com/en

Jabbour, C. J. C., De Sousa Jabbour, A. B. L., Govindan, K., Teixeira, A. A., & De Sousa Freitas, W. R. (2013). Environmental management and operational performance in automotive companies in Brazil: the role of human resource management and lean manufacturing. *Journal of Cleaner Production*, *47*(1), 129–140.

Junior, M. L., & Filho, M. G. (2012). Production planning and control for remanufacturing: literature review and analysis. *Production Planning & Control*, *23*(6), 419–435.

Kimms, A. (1998). Stability measures for rolling schedules with applications to capacity expansion planning, master production scheduling, and lot sizing. *International Journal of Management Science*, *26*(3), 355–366.

King, P. L. (2011). Crack the code: understanding safety stock and mastering its equations. *APICS Magazine*, 33–36.

Kjellsdotter-Ivert, L., & Jonsson, P. (2010). The potential benefits of advanced planning and scheduling systems in sales and operations planning. *Industrial Management & Data Systems*, *110*(5), 659–681.

Körpeoglu, E., Yaman, H., & Aktürk, M. S. (2011). A multi-stage stochastic programming approach in master production scheduling. *European Journal of Operational Research*, *213*(1), 166–179.

Lang Wood, J. (2012). Disadvantages of lean manufacturing. Retrieved August 13, 2015, from http://www.ehow.com/list_6025715_disadvantages-lean-manufacturing.html

Leung, M. (2009). *Production scheduling optimization of a plastics compounding plant with quality constraints* (Master thesis). University of Waterloo, Waterloo.

Liker, J. K. (1997). *Becoming lean: inside stories of US manufacturers* (1st ed.). New York: Productivity Press.

Mannino, C., Nilssen, E. J., & Nordlander, T. E. (2012). A pattern based, robust approach to cyclic master surgery scheduling. *Journal of Scheduling*, *15*(1), 553–563.

Mansouri, S. A., Gallear, D., & Askariazad, M. H. (2012). Decision support for build-to-order supply chain management through multiobjective optimization. *International Journal of Production Economics*, *135*(1), 24–36.

Maravelias, C. T., & Sung, C. (2009). Integration of production planning and scheduling: overview, challenges and opportunities. *Computers and Chemical Engineering*, *33*(1), 1919–1930.

Mula, J., Poler, R., García-Sabater, J. P., & Lario, F. C. (2006). Models for production planning under uncertainty: a review. *International Journal of Production Economics*, *103*(1), 271–285.

Nayab, N. (2011, August 2). Criticism of lean manufacturing. Retrieved August 13, 2015, from http://www.brighthubpm.com/methods-strategies/105933-criticism-of-lean-manufacturing/

Nedaei, H., & Mahlooji, H. (2014). Joint multi-objective master production scheduling and rolling horizon policy analysis in make-to-order supply chains. *International Journal of Production Research*, *52*(9), 2767–2787.

Nordin, N., Deros, B. M. D., & Wahab, D. A. (2010). A survey on lean manufacturing implementation in Malaysian automotive industry. *International Journal of Innovation, Management and Technology*, *1*(4), 374–380.

Omar, M. K., & Bennell, J. A. (2009). Revising the master production schedule in a HPP framework context. *International Journal of Production Research*, *47*(20), 5857–5878.

Pavlínek, P. (2012). The internationalization of corporate R&D and the automotive industry R&D of East-Central-Europe. *Economic Geography*, *88*(3), 279–310.

Peidro, D., Mula, J., Poler, R., & Lario, F. C. (2009). Quantitative models for supply chain planning under uncertainty: a review. *International Journal of Advanced Manufacturing Technology*, *43*(1), 400–420.

Robinson, E. P., Sahin, F., & Gao, L. L. (2008). Master production schedule time interval strategies in make-to-order supply chains. *International Journal of Production Research*, *46*(7), 1933–1954.

Rocco, C. D., & Morabito, R. (2014). Scheduling of production and logistics operations of steam production systems in food industries: a case study of the tomato processing industry. *Journal of the Operational Research Society*, *65*(1), 1896–1904.

Rother, M., & Shook, J. (1999). *Learning to see: value stream mapping to add value and eliminate muda* (1st ed.). Brookline: The Lean Enterprise Institute.

Sahin, F., Robinson, E. P., & Gao, L. L. (2008). Master production scheduling policy and rolling schedules in a two-stage make-to-order supply chain. *International Journal of Production Economics*, *115*(1), 528–541.

Sawik, T. (2007). Multi-objective master production scheduling in make-to-order manufacturing. *International Journal of Production Research*, *45*(12), 2629–2653.

Schwarz, M. (2008). *Trends in the automotive industry: implications on supply chain management* (pp. 1–6). San Jose: Cisco Internet Business Solutions Group.

Shpak, S. (2015, August 13). Advantages and disadvantages of lean production. Retrieved August 3, 2015, from http://smallbusiness.chron.com/advantages-amp-disadvantages-lean-production-46696.html

Sillekens, T., Koberstein, A., & Suhl, L. (2011). Aggregate production planning in the automotive industry with special consideration of workforce flexibility. *International Journal of Production Research*, *49*(17), 5055–5078.

Silver, E. A., Pyke, D. F., & Peterson, R. (1998). *Inventory management and production planning and scheduling* (3rd ed.). New York: Wiley.

Sneijkers, D. (2015, May 21). Analysis of current situation of production planning at IRS Venray.

Soares, M. M., & Vieira, G. E. (2009). A new multi-objective optimization method for master production scheduling problems based on genetic algorithm. *International Journal of Advanced Manufacturing Technology*, *41*(1), 549–567.

Song, D., Zhang, J., & Shi, J. (2012). Adaptive production scheduling for a make-to-order DNA manufacturing system. In *Proceedings of the 2012 Industrial and Systems Engineering Research Conference* (pp. 1–10). Fargo: North Dakota State University.

Sridharan, S. V., Berry, W. L., & Udayabhanu, V. (1988). Measuring master production schedule stability under rolling planning horizons. *Decision Sciences*, *19*(1), 147–167.

Sturgeon, T. J., Memedovic, O., Van Biesebroeck, J., & Gereffi, G. (2009). Globalization of the automotive industry: main features and trends. *International Journal of Technological Learning, Innovation and Development*, *2*(1), 7–24.

Sturgeon, T. J., Van Biesebroeck, J., & Gereffi, G. (2008). Value chains, networks and clusters: reframing the global automotive industry. *Journal of Economic Geography*, *8*(1), 294–321.

Taj, S. (2008). Lean manufacturing performance in China: assessment of 65 manufacturing plants. *Journal of Manufacturing Technology*, *19*(2), 217–234.

Teo, C. C., Bhatnagar, R., & Graves, S. C. (2011). Setting planned lead times for a make-to-order production system with master schedule smoothing. *IIE Transactions*, *43*(1), 399–414.

Teo, C. C., Bhatnagar, R., & Graves, S. C. (2012). An application of master schedule smoothing and planned lead time control. *Production and Operations Management*, *21*(2), 211–223.

Thompson, G. M. (1995). Labor scheduling using NPV estimates of the marginal benfit of additional labor capacity. *Journal of Operations Management*, *13*(1), 67–86.

Thun, J. H., & Hoenig, D. (2012). An empirical analysis of supply chain risk management in the German automotive industry. *International Journal of Production Economics*, *131*(1), 242–249.

Van den Bergh, J., Beliën, J., De Breucker, P., Demeulemeester, E., & De Boeck, L. (2013). Personnel scheduling: A literature review. *European Journal of Operational Research*, *226*(1), 367–385.

Vanhoucke, M., & Debels, D. (2009). A finite-capacity production scheduling procedure for a Belgian steel company. *International Journal of Production Research*, *47*(3), 561–584.

Vargas, V., & Metters, R. (2011). A master production scheduling procedure for stochastic demand and rolling planning horizons. *International Journal of Production Economics*, *131*(1), 296–302.

Vieira, G. E., & Ribas, P. C. (2008). Fractional factorial analysis to the configuration of simulated annealing applied to the multi-objective optimization of master production scheduling problems. *International Journal of Production Research*, *46*(11), 3007–3026.

Vollenberg, C. (2015, April 29). Orientation on the production planning process at IRS Venray.

Volling, T., Matzke, A., Grunewald, M., & Spengler, T. S. (2013). Planning of capacities and orders in build-to-order automobile production: a review. *European Journal of Operational Research*, *224*(1), 240–260.

Volling, T., & Spengler, T. S. (2011). Modeling and simulation of order-driven planning policies in build-to-order automobile production. *International Journal of Production Economics*, *131*(1), 183–193.

Wongwiwat, A., & Bohez, E. L. J. (2013). Production scheduling for injection molding manufacture using Petri Net model. *Assembly Automation*, *33*(3), 282–293.

Zobolas, G. I., Tarantilis, C. D., & Ioannou, G. (2008). Extending capacity planning by positive lead times and optional overtime, earliness and tardiness for effective master production scheduling. *International Journal of Production Research*, *46*(12), 3359–3386.

Appendix A. Organizational Information of IRS

ww.inalfa-roofsystems.com/en/company/

Figure 10: The different locations of Inalfa Roof Systems Group B.V.

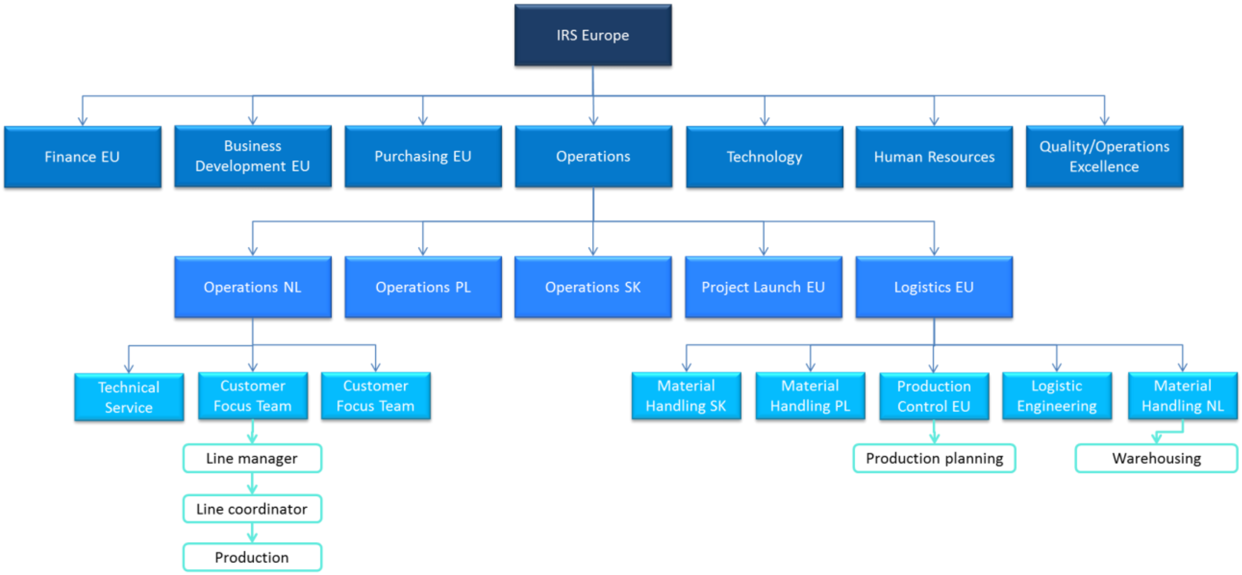
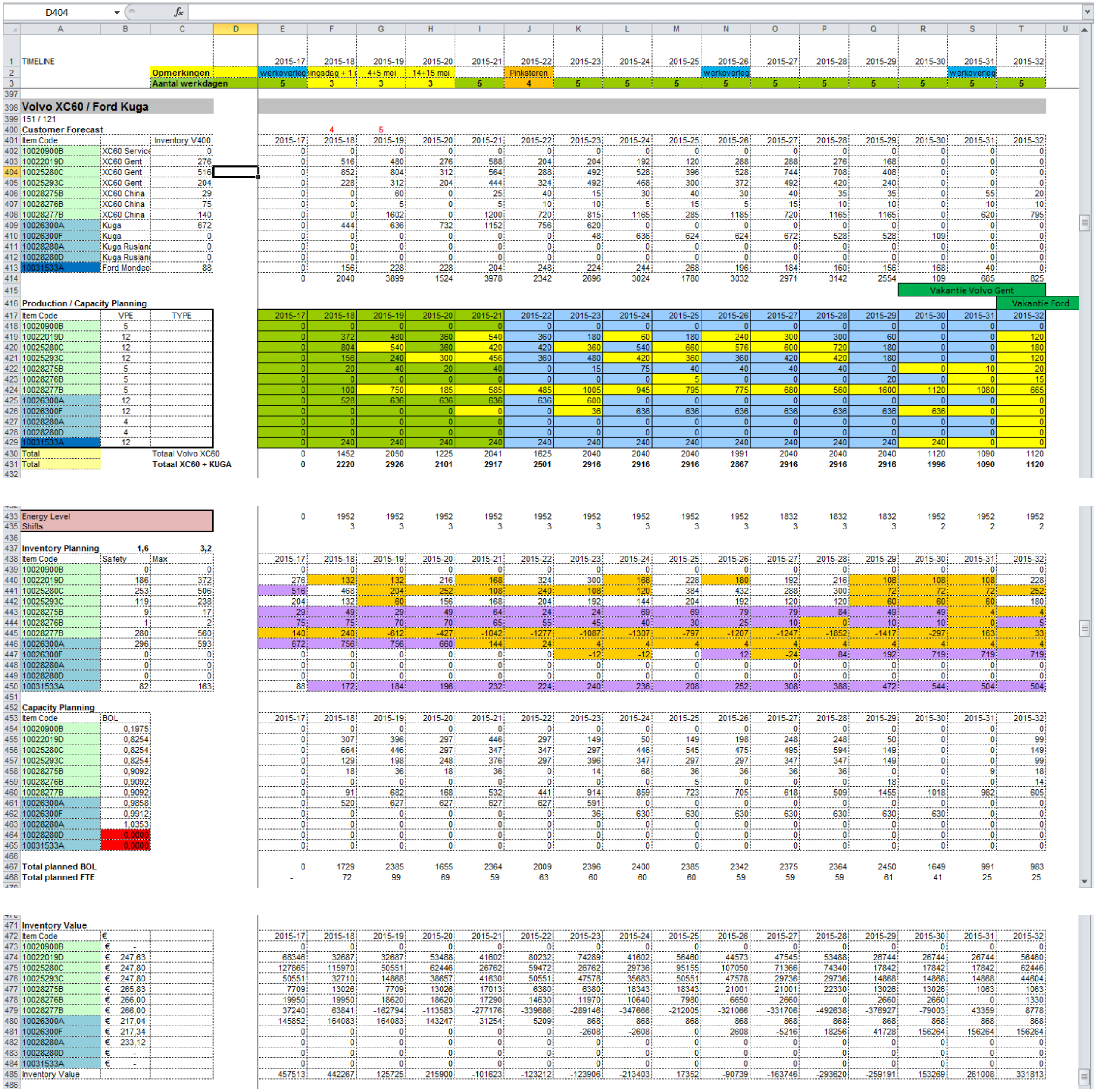


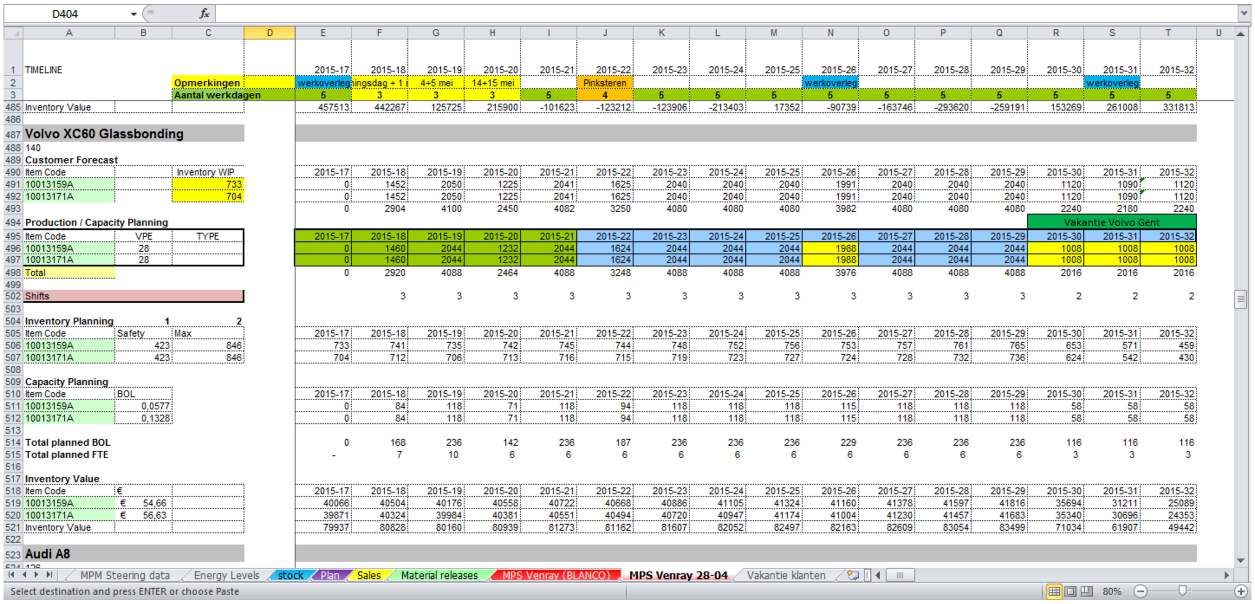
Figure 11: Organizational chart of the European department of Inalfa Roof Systems.

Appendix B. Excel File Used for MPS Calculation



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	TIMELINE				2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
2			**Opmerkingen**		werkoverleg	ingsdag + 1	4+5 mei	14+15 mei		Pinksteren				werkoverleg					werkoverleg	
3			**Aantal werkdagen**		**5**	**3**	**3**	**3**	**5**	**4**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**
397																				
398	**Volvo XC60 / Ford Kuga**																			
399	151 / 121																			
400	**Customer Forecast**					4	5													
401	Item Code		Inventory V400		2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
402	10020900B	XC60 Service	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
403	10022019D	XC60 Gent	276		0	516	480	276	588	204	204	192	120	288	288	276	168	0	0	0
404	10025280C	XC60 Gent	516		0	852	804	312	564	288	492	528	396	528	744	708	408	0	0	0
405	10025293C	XC60 Gent	204		0	228	312	204	444	324	492	468	300	372	492	420	240	0	0	0
406	10028275B	XC60 China	29		0	0	60	0	25	40	15	30	40	30	40	35	35	0	55	20
407	10028276B	XC60 China	75		0	0	5	0	5	10	10	5	15	5	15	10	10	0	10	10
408	10028277B	XC60 China	140		0	0	1602	0	1200	720	815	1165	285	1185	720	1165	1165	0	620	795
409	10026300A	Kuga	672		0	444	636	732	1152	756	620	0	0	0	0	0	0	0	0	0
410	10026300F	Kuga	0		0	0	0	0	0	0	48	636	624	624	672	528	528	109	0	0
411	10028280A	Kuga Ruslan	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
412	10028280D	Kuga Ruslan	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
413	10031533A	Ford Mondeo	88		0	156	228	228	204	248	224	244	268	196	184	160	156	168	40	0
414					0	2040	3899	1524	3978	2342	2696	3024	1780	3032	2971	3142	2554	109	685	825
415																		Vakantie Volvo Gent		
416	**Production / Capacity Planning**																			Vakantie Ford
417	Item Code	VPE	TYPE		2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
418	10020900B	5			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
419	10022019D	12			0	372	480	360	540	360	180	60	180	240	300	300	60	0	0	120
420	10025280C	12			0	804	540	360	420	420	360	540	660	576	600	720	180	0	0	180
421	10025293C	12			0	156	240	300	456	360	480	420	360	360	420	420	180	0	0	120
422	10028275B	5			0	20	40	20	40	0	15	75	40	40	40	40	0	0	10	20
423	10028276B	5			0	0	0	0	0	0	0	0	5	0	0	0	20	0	0	15
424	10028277B	5			0	100	750	185	585	485	1005	945	795	775	680	560	1600	1120	1080	665
425	10026300A	12			0	528	636	636	636	636	600	0	0	0	0	0	0	0	0	0
426	10026300F	12			0	0	0	0	0	0	36	636	636	636	636	636	636	636	0	0
427	10028280A	4			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
428	10028280D	4			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
429	10031533A	12			0	240	240	240	240	240	240	240	240	240	240	240	240	240	0	0
430	Total		Totaal Volvo XC60		0	1452	2050	1225	2041	1625	2040	2040	2040	1991	2040	2040	2040	1120	1090	1120
431	Total		**Totaal XC60 + KUGA**		**0**	**2220**	**2926**	**2101**	**2917**	**2501**	**2916**	**2916**	**2916**	**2867**	**2916**	**2916**	**2916**	**1996**	**1090**	**1120**
432																				
433	Energy Level				0	1952	1952	1952	1952	1952	1952	1952	1952	1952	1832	1832	1832	1952	1952	1952
435	Shifts					3	3	3	3	3	3	3	3	3	3	3	3	2	2	2
436																				
437	**Inventory Planning**	**1,6**	**3,2**																	
438	Item Code	Safety	Max		2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
439	10020900B	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
440	10022019D	186	372		276	132	132	216	168	324	300	168	228	180	192	216	108	108	108	228
441	10025280C	253	506		516	468	204	252	108	240	108	120	384	432	288	300	72	72	72	252
442	10025293C	119	238		204	132	60	156	168	204	192	144	204	192	120	120	60	60	60	180
443	10028275B	9	17		29	49	29	49	64	24	24	69	69	79	79	84	49	49	4	4
444	10028276B	1	2		75	75	70	70	65	55	45	40	30	25	10	0	10	10	0	5
445	10028277B	280	560		140	240	-612	-427	-1042	-1277	-1087	-1307	-797	-1207	-1247	-1852	-1417	-297	163	33
446	10026300A	296	593		672	756	756	660	144	24	4	4	4	4	4	4	4	4	4	4
447	10026300F	0	0		0	0	0	0	0	0	-12	-12	0	12	-24	84	192	719	719	719
448	10028280A	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
449	10028280D	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
450	10031533A	82	163		88	172	184	196	232	224	240	236	208	252	308	388	472	544	504	504
451																				
452	**Capacity Planning**																			
453	Item Code	BOL			2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
454	10020900B	0,1975			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
455	10022019D	0,8254			0	307	396	297	446	297	149	50	149	198	248	248	50	0	0	99
456	10025280C	0,8254			0	664	446	297	347	347	297	446	545	475	495	594	149	0	0	149
457	10025293C	0,8254			0	129	198	248	376	297	396	347	297	297	347	347	149	0	0	99
458	10028275B	0,9092			0	18	36	18	36	0	14	68	36	36	36	36	0	0	9	18
459	10028276B	0,9092			0	0	0	0	0	0	0	0	5	0	0	0	18	0	0	14
460	10028277B	0,9092			0	91	682	168	532	441	914	859	723	705	618	509	1455	1018	982	605
461	10026300A	0,9858			0	520	627	627	627	627	591	0	0	0	0	0	0	0	0	0
462	10026300F	0,9912			0	0	0	0	0	0	36	630	630	630	630	630	630	630	0	0
463	10028280A	1,0353			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
464	10028280D	0,0000			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
465	10031533A	0,0000			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
466																				
467	**Total planned BOL**				0	1729	2385	1655	2364	2009	2396	2400	2385	2342	2375	2364	2450	1649	991	983
468	**Total planned FTE**				-	72	99	69	59	63	60	60	60	59	59	59	61	41	25	25
471	**Inventory Value**																			
472	Item Code	€			2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
473	10020900B	€ -			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
474	10022019D	€ 247,63			68346	32687	32687	53488	41602	80232	74289	41602	56460	44573	47545	53488	26744	26744	26744	56460
475	10025280C	€ 247,80			127865	115970	50551	62446	26762	59472	26762	29736	95155	107050	71366	74340	17842	17842	17842	62446
476	10025293C	€ 247,80			50551	32710	14868	38657	41630	50551	47578	35683	50551	47578	29736	29736	14868	14868	14868	44604
477	10028275B	€ 265,83			7709	13026	7709	13026	17013	6380	6380	18343	18343	21001	21001	22330	13026	13026	1063	1063
478	10028276B	€ 266,00			19950	19950	18620	18620	17290	14630	11970	10640	7980	6650	2660	0	2660	2660	0	1330
479	10028277B	€ 266,00			37240	63841	-162794	-113583	-277176	-339686	-289146	-347666	-212005	-321066	-331706	-492638	-376927	-79003	43359	8778
480	10026300A	€ 217,04			145852	164083	164083	143247	31254	5209	868	868	868	868	868	868	868	868	868	868
481	10026300F	€ 217,34			0	0	0	0	0	0	-2608	-2608	0	2608	-5216	18256	41728	156264	156264	156264
482	10028280A	€ 233,12			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
483	10028280D	€ -			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
484	10031533A	€ -			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
485	Inventory Value				457513	442267	125725	215900	-101623	-123212	-123906	-213403	17352	-90739	-163746	-293620	-259191	153269	261008	331813
486																				

Figure 12: MPS planning sheet used at IRS for the XC60/Kuga/Mondeo-line (part of the whole file for all assembly lines)



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	TIMELINE				2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
2			Opmerkingen		werkoverleg	ingsdag + 1	4+5 mei	14+15 mei		Pinksteren				werkoverleg					werkoverleg	
3			Aantal werkdagen		5	3	3	3	5	4	5	5	5	5	5	5	5	5	5	5
485	Inventory Value				457513	442267	125725	215900	-101623	-123212	-123906	-213403	17352	-90739	-163746	-293620	-259191	153269	261008	331813
486																				
487	**Volvo XC60 Glassbonding**																			
488	140																			
489	**Customer Forecast**																			
490	Item Code		Inventory WIP		2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
491	10013159A		733		0	1452	2050	1225	2041	1625	2040	2040	2040	1991	2040	2040	2040	1120	1090	1120
492	10013171A		704		0	1452	2050	1225	2041	1625	2040	2040	2040	1991	2040	2040	2040	1120	1090	1120
493					0	2904	4100	2450	4082	3250	4080	4080	4080	3982	4080	4080	4080	2240	2180	2240
494	**Production / Capacity Planning**																	Vakantie Volvo Gent		
495	Item Code	VPE	TYPE		2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
496	10013159A	28			0	1460	2044	1232	2044	1624	2044	2044	2044	1988	2044	2044	2044	1008	1008	1008
497	10013171A	28			0	1460	2044	1232	2044	1624	2044	2044	2044	1988	2044	2044	2044	1008	1008	1008
498	Total				0	2920	4088	2464	4088	3248	4088	4088	4088	3976	4088	4088	4088	2016	2016	2016
499																				
502	Shifts					3	3	3	3	3	3	3	3	3	3	3	3	2	2	2
503																				
504	**Inventory Planning**	**1**	**2**																	
505	Item Code	Safety	Max		2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
506	10013159A	423	846		733	741	735	742	745	744	748	752	756	753	757	761	765	653	571	459
507	10013171A	423	846		704	712	706	713	716	715	719	723	727	724	728	732	736	624	542	430
508																				
509	**Capacity Planning**																			
510	Item Code	BOL			2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
511	10013159A	0,0577			0	84	118	71	118	94	118	118	118	115	118	118	118	58	58	58
512	10013171A	0,1328			0	84	118	71	118	94	118	118	118	115	118	118	118	58	58	58
513																				
514	**Total planned BOL**				0	168	236	142	236	187	236	236	236	229	236	236	236	116	116	116
515	**Total planned FTE**				-	7	10	6	6	6	6	6	6	6	6	6	6	3	3	3
516																				
517	**Inventory Value**																			
518	Item Code	€			2015-17	2015-18	2015-19	2015-20	2015-21	2015-22	2015-23	2015-24	2015-25	2015-26	2015-27	2015-28	2015-29	2015-30	2015-31	2015-32
519	10013159A	€ 54,66			40066	40504	40176	40558	40722	40668	40886	41105	41324	41160	41378	41597	41816	35694	31211	25089
520	10013171A	€ 56,63			39871	40324	39984	40381	40551	40494	40720	40947	41174	41004	41230	41457	41683	35340	30696	24353
521	Inventory Value				79937	80828	80160	80939	81273	81162	81607	82052	82497	82163	82609	83054	83499	71034	61907	49442
522																				
523	**Audi A8**																			

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Figure 13: MPS planning sheet used at IRS for the XC60 glass bonding process (part of the whole file for all assembly lines)

Appendix C. Classification of MPS Literature

Table 23: Classification of recent MPS literature

		Problem Characteristics						Problem Constraints					Solution Approaches					MPS Design Parameters			Performance Measures			
Article	**Sector**	*Type of production system*	*Demand*	*# production lines*	*# products*	*Production yield*	*Backorders*	*Demand fulfillment requirement*	*Inventory*	*Capacity*	*Workforce*	*Set up*	*Type of solution model*	*Hierarchical production planning*	*Workforce*	*Adjustable capacity*	*Inventory*	*Planning horizon*	*Frozen period*	*Review frequency*	*Profit/Costs*	*Service level*	*Schedule leveling*	*Production flexibility*
Barlatt et al. (2009)	*Automotive*	FS	D	ML	MP			x	x		x	x	MP		x	x	x				C			
Dörmer et al. (2015)		FS	D	SL	MP					x			MP		x		x				C		x	
Garcia-Sabater et al. (2012)		FL	D	ML	MP		x	x	x	x		x	MP	x			x				C		x	
Körpeoglu et al. (2011)		FS	SS	SL	MP		x			x			MP			x	x				P			
Sillekens et al. (2011)		FS	SS	SL	MP	x		x				x	MP		x	x	x				C			x
Volling & Spengler (2011)		FL	ED	SL	SP					x			SIM	x			x				C	x	x	
Gahm et al. (2014)	*Capital Goods*	JS	D	ML	MP			x		x	x		HEU		x				x		C	x	x	
Teo et al. (2012)		JS	S	ML	MP			x		x			MP		x		x	x			C		x	
Song et al. (2012)	*Flow Shop*	FS	S	SL	MP	x	x			x			SIM				x				P	x		
Wongwiwat et al. (2013)		JS	SS	ML	MP					x			SIM			x						x		
Beliën et al. (2009)	*Health Care*	FL	ED	ML	MP					x			MP										x	
Mannino et al. (2012)		FL	S	ML	MP					x			MP								C	x		
Vanhoucke & Debels (2009)	*Metal production*	FS	S	ML	MP		x		x	x			SIM	x		x	x				C			
Leung (2009)	*Process Industry*	FL	D	ML	MP	x	x	x		x		x	MP				x				C			
Omar & Bennell (2009)		FL	S	ML	MP		x		x	x		x	MP	x	x	x	x			x	C			
Rocco & Morabito (2014)		FL	D	SL	SP			x	x	x		x	MP	x		x	x	x			C			

Article	Sector	Problem Characteristics						Problem Constraints					Solution Approaches					MPS Design Parameters			Performance Measures			
		Type of production system	Demand	# production lines	# products	Production yield	Backorders	Demand fulfillment requirement	Inventory	Capacity	Workforce	Set up	Type of solution model	Hierarchical production planning	Workforce	Adjustable capacity	Inventory	Planning horizon	Frozen period	Review frequency	Profit/Costs	Service level	Schedule leveling	Production flexibility
Dhingra & Chandna (2010)	*Theoretical*	**FS**	**D**	**ML**	**MP**		**x**			**x**		**x**	**SIM**				**x**				**C**	**x**		
Feng et al. (2011)		**FL**	**S**	**SL**	**SP**		**x**			**x**			**MP**				**x**				**C**	**x**		
Nedaei & Mahlooji (2014)		**FL**	**S**	**SL**	**SP**		**x**						**SIM**				**x**	**x**	**x**	**x**	**C**	**x**	**x**	
Robinson et al. (2008)		**FL**	**S**	**SL**	**SP**								**SIM**				**x**	**x**	**x**	**x**	**C**		**x**	**x**
Sahin et al. (2008)		**FL**	**D**	**SL**	**SP**								**SIM**				**x**	**x**	**x**	**x**	**C**		**x**	
Sawik (2007)		**FS**	**D**	**ML**	**MP**		**x**	**x**		**x**			**MP**				**x**					**x**	**x**	
Soares & Vieira (2009)		**JS**	**SS**	**ML**	**MP**					**x**			**GA**				**x**				**C**	**x**		
Teo et al. (2011)		**FS**	**S**	**ML**	**MP**		**x**	**x**		**x**			**MP**		**x**		**x**	**x**			**C**		**x**	
Vargas & Metters (2011)		**FL**	**S**	**SL**	**SP**		**x**	**x**				**x**	**HEU**			**x**	**x**	**x**			**C**			
Vieira & Ribas (2008)		**JS**	**SS**	**ML**	**MP**		**x**			**x**			**SIM**				**x**				**C**	**x**		
Zobolas et al. (2008)		**JS**	**ED**	**ML**	**MP**		**x**		**x**	**x**			**GA**		**x**		**x**				**C**			

Explanation of the abbreviations: *Flow Line (**FL**), Flow Shop (**FS**), Job Shop (**JS**), Deterministic (**D**), Stochastic (**S**), Specified Scenario (**SS**), Empirical Data (**ED**), Single Line (**SL**), Multiple Line (**ML**), Single Product (**SP**), Multiple Product (**MP**), Mathematical Programming (**MP**), Simulation (**SIM**), Heuristics (**HEU**), Genetic Algorithm (**GA**), Profit (**P**), Costs (**C**), Specifically included in research (**x**).*

Appendix D. Methodology

This research is mainly divided into three stages; an analysis phase (section 3), a method development phase (section 4), and the application of the developed method in the case study phase (section 5).

In the analysis phase an overview of characteristics of the production- and the planning process is give, in order to delineate the specific requirements to cope with the production planning problem faced by IRS. The characteristics of the production environment and the assumptions currently made for the planning of production serve as an input for the improvement efforts. The production environment defines the constraints and opportunities of the developed model, while the planning process is analyzed to reveal areas of improvement. Furthermore, an evaluation of the demand is given, such that its characteristics can be taken into account during the development of a planning method. Also, an outline of the current performance of IRS is given. The current performance is measured under the same assumptions as the results of the case study are measured. This is to assure that a good comparison between the current situation and the improvements can be made.

In the method development phase, two models are built to improve the production planning of IRS, but more importantly to create a general production planning model for production companies such as IRS. Two models are developed of which the first model is an extensive model that plans production capacity per production station. The second model is a relaxation of this model, such that it is more useful in practice for IRS and that is easier to use for the analysis made in the case study phase.

Lastly, in the case study phase, the simplified model is used in the pursue of two goals; (1) comparing the improvement of the developed model and the current situation at IRS, and (2) analyzing the influence of the parameters in the model on the models behavior. First, the model's parameters are set to IRS's estimated real-life values. This represents the initial reference model, and the actual situation faced at IRS. Next, one parameter at a time is adjusted in the reference model and their results are compared in a sensitivity analysis. Hence, the influence of the parameters on the models behavior is investigated and a more optimal model is sought. Each model is compared to the current performance of IRS and to the reference model.

Data Collection

Data is mainly retrieved from the ERP system of IRS or from other ICT sources that are used in the company. Furthermore, data is completed by means of interviews or measurements whenever possible and appropriate. The data is made available by the managers of the logistics and operations departments. The data horizons are limited, since IRS changed its ERP system in the spring of 2014 and lots of data was considered not reliable or simply lost. Therefore, it is chosen to use reliable data only to guarantee the validity of this research. The following quantitative datasets are used for this research (all data is aggregated to weeks):

- Demand data: week 22-2014 until week 31-2015 (62 weeks)
- MPS schedule data: week 22-2014 until week 44-2015 (75 weeks)
- Cost performance data: week 01-2015 until week 31-2015 (31 weeks)
- System performance data: week 01-2015 until week 47-2015 (47 weeks)
- Test period data: week 37-2015 until week 47-2015 (10 weeks)
- Demand forecasts June 2015 until May 2016 (12 months)

Appendix E. Demand Characteristics Analysis

The four different roof systems all see their own demand patterns, as is depicted in Figure 14. The demand volumes shown in this picture are the weekly volumes that were ordered by IRS' customers.

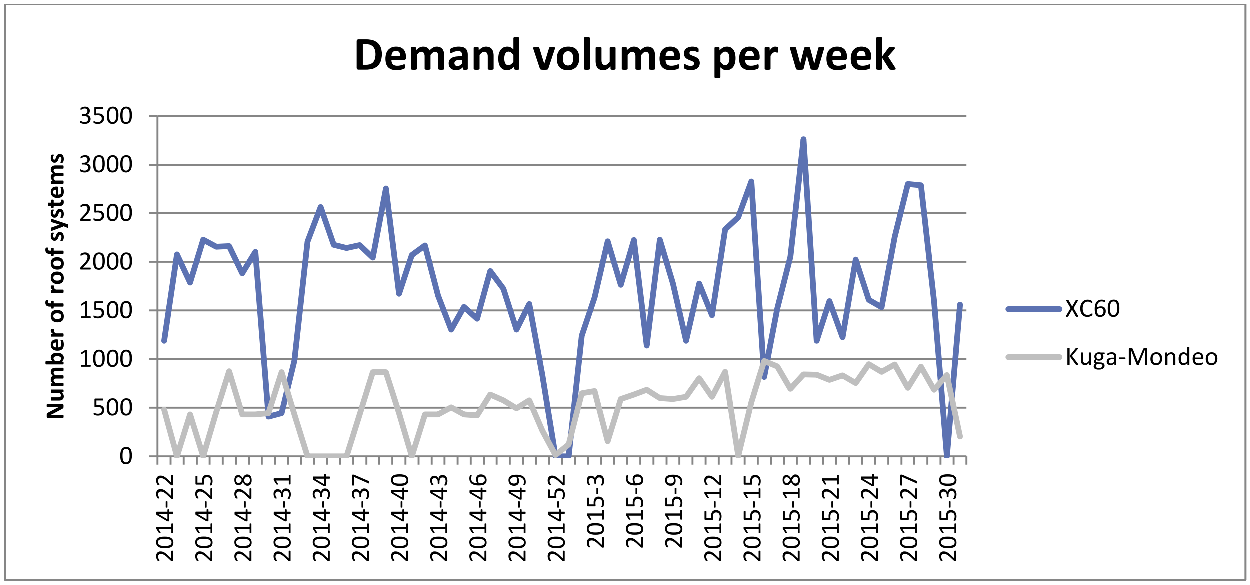


Figure 14: Weekly demand volumes of the XC60- and the Kuga-Mondeo roof systems

The average demand for XC60 roof systems is 1721 (*S.D. 682*) roofs per week and for Kuga-Mondeo it is 535 (*S.D. 295*) roofs per week (see Table 24). However, in this figures the weeks that the customer's factories were closed, due to holidays, and no demand was see in included in these averages. When adjusting for the number of closing weeks, the averages are 1809 (*S.D. 575*) and 623 (*S.D. 220*) roofs per week respectively, for XC60 roof systems and Kuga-Mondeo systems. Since these closing weeks are due to holidays they can be considered outliers. Therefore, when regarding the standard deviation of the demand, the vacation adjusted data is more representative. Also, the trend in demand per roof system type is more representative in the vacation adjusted data set, which can be also retrieved in Table 24.

Table 24: Demand characteristics per roof type

	Full year				**Vacation adjusted**			
Type	**Total**	**Average**	**Std. Dev.**	**Trend**	**weeks closed**	**Average**	**Std. Dev.**	**Trend**
XC60 (Gent)	67958	1096	521	-3	7	1236	365	-4
XC60 (China)	38752	625	505	3	10	745	463	11
XC60 Total	*106710*	*1721*	*682*	*0*	*3*	*1809*	*575*	*3*
Kuga	30477	492	260	6	7	586	163	3
Mondeo	2667	178	64	-7	1	189	50	-3
Ford Total	*33144*	*535*	*295*	*8*	*7*	*623*	*220*	*8*
TOTAL	**139890**	**2256**	**744**	**8**	**2**	**2329**	**638**	**9**

Besides the demand average and variance, the volatility of the customer's demand forecasts plays an important role in the scheduling process. Since a 15-week rolling scheduling horizon is used, every change in demand volume for a given week during the planning horizon influences the re-scheduling process. Ideally, customer forecasts would not change over time when they are observed for the first time, resulting in deterministic demand with a supply lead time of fifteen weeks in the IRS case. However, in this period the demand changes over time. Several measures are used to measure the forecast instability; mean forecasting error (MFE), cumulative mean forecasting error (CMFE), mean absolute error (MAD), and cumulative mean absolute error (CMAD). The formulas and descriptions of the used measures are given in Table 25. The forecast error used in this measure is simply the change in demand between the one week and another. The measures chosen here are based on Kimms (1998), Sridharan, Berry, & Udayabhanu (1988) and general forecasting theory (Silver et al., 1998).

Table 25: Measures used to assess demand forecast fluctuation

Measure	Formula	Description
MFE	$\frac{\sum_{i=1}^{15} Forecast\ error}{15\ weeks}$	The average direction of change in demand per week.
CMFE	$\sum_{i=1}^{15} Forecast\ error$	The cumulative direction of change in demand (15 weeks).
MAD	$\frac{\sum_{i=1}^{15} \lvert Forecast\ error \rvert}{15\ weeks}$	The average total of change (negative and positive) in demand per week.
CMAD	$\sum_{i=1}^{15} \lvert Forecast\ error \rvert$	The cumulative total of change (negative and positive) in demand (15 weeks).

When analyzing the demand forecast it is notable that demand volumes for a given week (for example, week 20 in 2015) show major changes during the planning horizon. However, when we look at the average direction of the fluctuation it is rather small, implying that demand appears to be very volatile, while its average is reasonably stable (see Table 26). The average change in demand for a given week for one rescheduling effort is rather small (MFE = *-2* (Total)) compared to the absolute change in demand volume for a week (MAD = *301* (Total)). It can be concluded that customers make many last-minute changes, but these have only a small influence on long-term average demand. Therefore, it might be advisable to disregards short term changes and focus on long-term trends.

Table 26: Demand forecast fluctuation during the 15-week planning horizon

	MFE	CMFE	MAD	CMAD
XC60	-6	-76	301	3912
Kuga-Mondeo	10	131	168	2196
Total	**-2**	**-32**	**334**	**4343**

Normality Test

Especially regarding safety stock estimation, it is important to know the probability distribution of the demand to estimate the right safety stock. We assumed that demand was most likely to be normally distributed, when observing demand data as is depicted in Figure 15. Especially, the frequency graphs of XC60 demand and total demand show the bell shape that is associated with the normal distribution, however it are not perfect bell shapes. The Kuga-Mondeo demand shows a more random pattern. All sets of demand show multiple occurrences of very low demand compared to the mean. These are demand volumes in weeks that the customer’s plants were closed due to holidays.

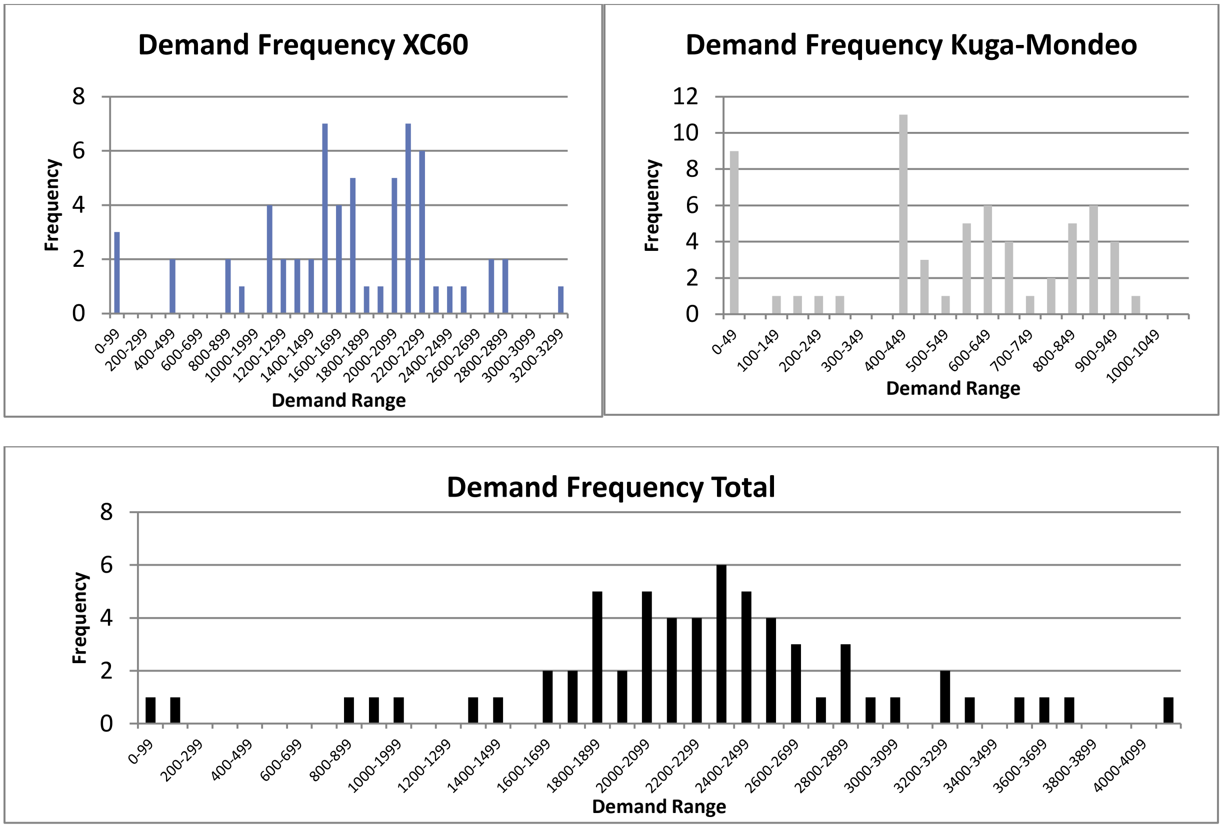
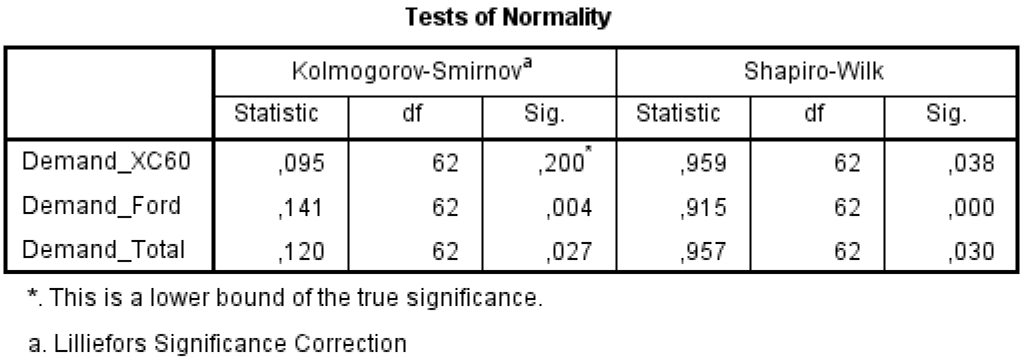


Figure 15: Frequencies for XC60-, Kuga-Mondeo- and Total demand

Next, the demand was statistically tested on normality, as is presented in Figure 16. Only the XC60 demand was proven to be normally distributed by the Kolomogorov-Smirov (KS) test (*p=0.20*), while the null-hypothesis was rejected for the Shapiro-Wilk (SW) test (*p=0.04*). The Kuga-Mondeo demand (KS: (*p=0.00*); SW: (*p=0.00*)) and the total demand (KS: (*p=0.03*); SW: (*p=0.03*)) were considered not normally distributed.



Tests of Normality

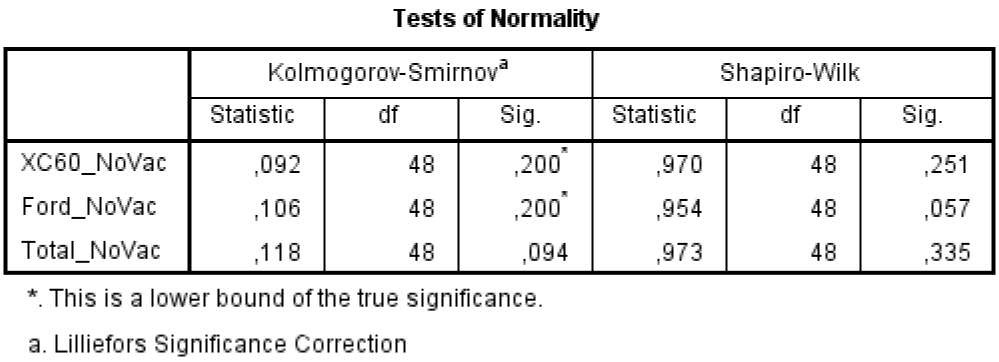
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Demand_XC60	,095	62	,200*	,959	62	,038
Demand_Ford	,141	62	,004	,915	62	,000
Demand_Total	,120	62	,027	,957	62	,030

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Figure 16: Test of normality for roof system demand (not corrected for outliers)

However, when extracting outliers from the dataset, namely the demand volumes in holiday periods, all demand patterns were proven to be normally distributed (see Figure 17). XC60 demand was proven on both KS-test (p=0.20) and SW-test (p=0.25) to be normally distributed. Kuga-Mondeo (KS: (*p=0.20*); SW: (*p=0.06*)) and total (KS: (*p=0.09*); SW: (*p=0.34*)) demands were proven significantly normally distributed.



Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
XC60_NoVac	,092	48	,200*	,970	48	,251
Ford_NoVac	,106	48	,200*	,954	48	,057
Total_NoVac	,118	48	,094	,973	48	,335

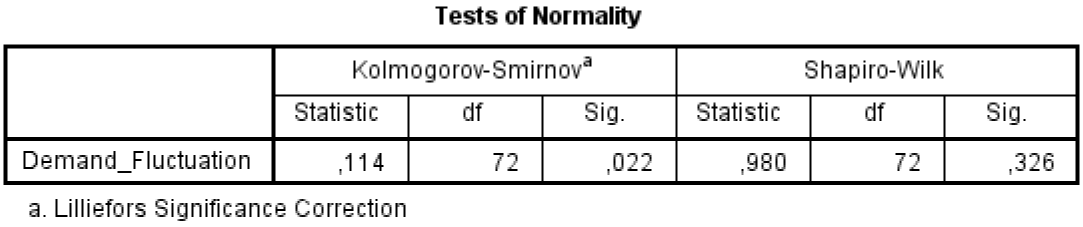
*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Figure 17: Test of normality for roof system demand (corrected for outliers)

Since, the outliers can be reasonably predicted in practice (closure of customer's factories is known in advance), we thus assume all demand faced by IRS to be normally distributed. This is used to calculate safety stocks for finished goods in section 5.1.

Lastly, the demand volatility was tested for normality, as is depicted in Figure 18. However only significantly distributed normal on the SW-test (*p=0.33*), and not significant on the KS-test (*p=0.02*), the demand volatility is assumed to be normal. This implies that the change in demand for a given week throughout the planning horizon that IRS faces, changes according to a normal distribution with a mean (CMFE) and standard deviation.



Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Demand_Fluctuation	,114	72	,022	,980	72	,326

a. Lilliefors Significance Correction

Figure 18: Test of normality for roof system demand volatilty

Appendix F. System Performance Analysis

The system performance regards a few aspects of the aggregate planning of IRS. The most important is whether demand is timely met, since late deliveries cause production stops at the customers. Those production stops cause high contractual penalty costs and must therefore be avoided. Furthermore, over-time work and emergency shipment costs are unnecessary additional costs that must be prevented, because they are, in general, very high compared to the regular working and shipment costs. In section 5.2 these costs are defined specifically for IRS. Lastly, the schedule stability and re-planning stability is measured, since significant changes in the production planning might cause difficulties in workforce or raw materials availability.

Redundant System Costs

Since IRS does not allow for backorders that cause production stops at their customers, the demand delivery performance is most visible in terms of emergency shipments and over-time work. This is the case since these are expensive emergency measures that prevent an out of stock situation at the customer and temporarily increase production capacity at IRS.

Between week 1 and week 31 of 2015 a total of €84,436 on emergency shipments are made, which are shown in Table 27. These were mostly due to a reduction in production capacity caused by quality problems; the production yield for the Kuga and Mondeo roof systems dropped below 75% between May and August (see Figure 6). To prevent production stops at the customer, extra transports were organized and overtime was worked to meet the delivery due dates. The capacity problems in the Kuga-Mondeo production also had its effect on the XC60 production due to rescheduling. Mostly, this roof system was produced in the weekend shifts (over-time). Therefore, in the period of week 1 until week 34 of 2015 16 Saturday shifts were worked and 2 Sunday shifts. Employees receive 150% of their normal wage at Saturday and 200% on Sunday. This resulted in an overtime cost of €89,006 (see Table 27). The regular production costs were €1,888,932 in this period. Hence, overtime costs were 4.71% of the total system costs and emergency shipment costs were 4.09% of the total system costs.

Table 27: Redundant costs for the XC60-Kuga-Mondeo production system

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Emergency Shipment costs	-	-	€2,034	€3,232	-	€42,046	€35.090	-
Overtime costs	€5,277	€1,778	€1,248	€5,195	€19,188	€37,120	€15,643	€4,785
# Saturday shifts	3	1	-	1	4	4	3	1
# Sunday shifts	-	-	-	-	-	2	-	-

The labor costs included in this analysis are purely direct labor costs, since indirect labor costs are too susceptible to interpretation and thus difficult to measure. Also, no reliable data is available for indirect labor. The total regular transportation costs are either not available. This is mainly due to the fact that IRS's customers organize the regular transports and costs are included in the sales prices of the roof systems.

System Costs

However the system redundant costs are the ones that are most desirable to reduce, they are not the only costs made while producing or planning. They merely stress the problems that have occurred at IRS and might be considered an incentive for improvement. Besides, they are not measurable for the case study tests that are performed in section 5.5. To be able to compare costs the costs that are made during the test period are presented below, in Table 28, to serve as zero measurement to compare the performance of the planning model that is developed in this thesis.

Table 28: Performance of the IRS production system during the test period

	XC60 stock	Kuga-Mondeo Stock	Permanent Workers	Contingent workers	# of hired	# of dismissed	Utilization	CMFE	CMAD	TOTAL
Average	1361	629	39	16	9	9	95,16%	1	6	
Cost	€ 18.411	€ 8.515	€ 516.516	€ 238.140	€ 30.618	€ 4.500				**€ 816.700**

The test period spans eleven periods with ten rescheduling efforts. In this period 39 permanent operators were employed and on average 16 contingent workers were hired. Production capacity was adjusted quite often, as can be concluded from the number of hired and dismissed workers. However, this is an assumption that replaces the over-time work that was needed to meet due dates. This assumption was made to align the measurement of the real-life costs in the testing period with the measurement costs. Over-time work costs were in this period actually €45,190, which is more than the hiring and dismissal costs of €35,118 presented above. These extra costs are incorporated in the extra numbers of employees that are scheduled on average, compared to the case study analysis results, which are explained in section 5.5. The total costs of the system for this period were €816,700.

Schedule and Re-planning Stability

The stability of the production plan might be considered important, since it makes the availability of employees better and more predictable. Especially, the re-planning stability is important in terms of workforce capacity planning. When the planning for a given week changes throughout the planning horizon managers have to re-schedule their employees, which might cause unavailability of the required number of workers or loss of goodwill, when employees are sent home or their shifts are cancelled in advance.

The final scheduled production quantities, compared to the total demand, are represented in Figure 19. The table shows that the production schedule is relatively volatile. The major decreases in planned orders are caused by holidays however. When visually comparing demand and production, the production output attempts to follow the demand pattern in a reduced manner.

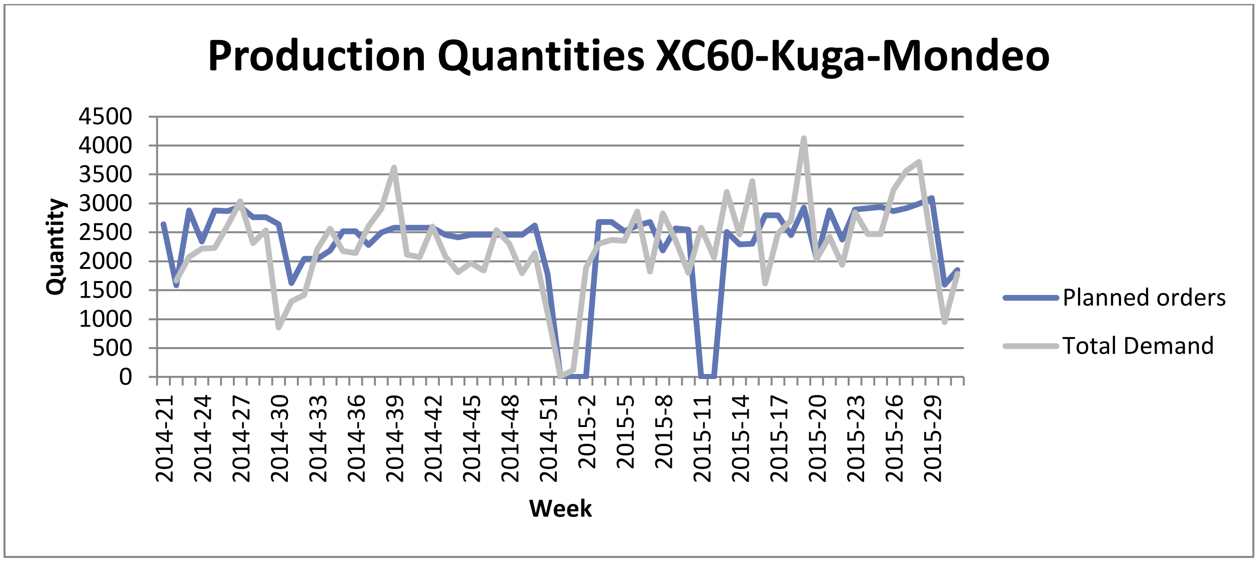


Figure 19: Definite total production quantities scheduled by IRS

Re-scheduling is considered as the change in planned production quantity after updating the production plan for a given week. When considering re-scheduling stability, the same measures are used as for demand forecast stability; MFE, CMFE, MAD, CMAD. However the concepts are the same, a different name is used since we are not measuring forecast stability, but schedule stability. Therefore the following names are used; mean re-scheduling error (MRSE), cumulative mean re-scheduling error (CMRSE), mean absolute re-scheduling deviation (MARSD), and cumulative mean absolute re-scheduling deviation (CMARSD). The outcomes are presented in Table 29.

Table 29: Scheduling stability measurements of the XC60-Kuga-Mondeo production system

	MRSE	CMRSE	MARSD	CMARSD
Schedule stability	-62	-3530	356	20294
Re-planning stability	-1	-13	64	831
Total	**-2**	**-32**	**334**	**4343**

When considering the results of this analysis, it becomes clear that the deviations in planned order are greater between weeks, than within a week over the time of the planning horizon. The most worrying conclusion is that the total average of change during the planning horizon for a given week is *831* (CMASD). This implies that on average the production quantity for a given week is rescheduled with *831* roof systems, however resulting of in an average change between the first and last week of re-planning of only *-13* roof systems. This indicates nervousness of the planning, while in the end the planned order quantity will remain quite the same. This is corresponds with the same measure outcomes as the demand forecast stability.

Appendix G. Demand Analysis Case Study

The demand patterns that are used for the case study are presented below. For both XC60 as Kuga-Mondeo demand, as well as the total cumulated demand the forecast are shown per week. The volatility in demand forecasts is shown, as well as the final demands for each week.

Table 30: Demand volatility of the testing period

Fluctuation	MFE	CMFE	MAD	CMAD
XC60	-27	41	240	1209
Kuga-Mondeo	13	10	128	554
Total	-14	51	297	1561

Table 31: XC60 demand during the testing period

		Planned for Week																							
	XC60	**2015-38**	**2015-39**	**2015-40**	**2015-41**	**2015-42**	**2015-43**	**2015-44**	**2015-45**	**2015-46**	**2015-47**	**2015-48**	**2015-49**	**2015-50**	**2015-51**	**2015-52**	**2015-53**	**2016-1**	**2016-2**	**2016-3**	**2016-4**	**2016-5**	**2016-6**	**2016-7**	**2016-8**
Planned in Week	**2015-37**	1665	2300	1606	2300	1548	2300	1983	2034	2300	1823	1217	1265	1722	746										
	2015-38		1588	1611	1988	2300	1988	2024	1993	1634	2189	1668	1253	1577	1016	750									
	2015-39			2000	1541	2050	2300	1210	2300	2038	2053	1205	1361	2074	739	695	435								
	2015-40				1625	2038	2300	1215	2064	2038	2300	1229	1205	2062	1123	850	870	728							
	2015-41					1642	2300	1630	2026	2079	2084	1229	1637	1625	998	870	435	634	1264						
	2015-42																								
	2015-43							1608	2089	2077	1608	1596	1188	2053	715	865	435	1227	1227	893	2300				
	2015-44								2000	1995	2300	1188	1224	1644	804	855	435	1359	1259	1133	2300	1349			
	2015-45									1893	2059	1198	1234	1619	1819	555	550	784	884	1800	2300	1165	1452		
	2015-46										2064	1234	1608	1663	1808	625	755	788	1404	1384	2300	1175	1229	2057	
	2015-47											1608	1596	1478	1658	625	690	788	1121	2027	1981	1187	2052	1744	2228

Table 32: Kuga-Mondeo demand during the testing period

		Planned for Week																							
	Kuga-Mondeo	**2015-38**	**2015-39**	**2015-40**	**2015-41**	**2015-42**	**2015-43**	**2015-44**	**2015-45**	**2015-46**	**2015-47**	**2015-48**	**2015-49**	**2015-50**	**2015-51**	**2015-52**	**2015-53**	**2016-1**	**2016-2**	**2016-3**	**2016-4**	**2016-5**	**2016-6**	**2016-7**	**2016-8**
Planned in Week	**2015-37**	1040	493	1040	591	1040	1040	1040	1040	983	1027	1031	601	927	966										
	2015-38		1018	430	491	1040	1040	1040	1040	1040	1040	1040	632	1034	1040	569									
	2015-39			783	383	1040	1040	1040	1040	1040	1040	1040	655	1040	1011	574	0								
	2015-40				600	384	1040	1040	1040	1040	1040	1040	631	1026	1040	469	0	0							
	2015-41					912	360	1040	1040	1040	1040	1040	588	972	1008	528	0	960	1040						
	2015-42																								
	2015-43							1020	576	1040	1040	1040	636	1008	996	540	0	1020	1040	1040	1032				
	2015-44								840	668	1040	1040	768	1040	1040	600	0	1020	1040	1040	840	948			
	2015-45									900	456	1040	840	1040	1040	576	0	1032	1040	1040	1040	960	1032		
	2015-46										972	528	660	996	924	600	0	1040	1040	1040	1020	1040	924	1040	
	2015-47											1040	480	1040	1040	0	549	1040	1040	1040	1040	1040	1040	936	1040

Table 33: Total demand during the testing period

		Planned for Week																							
	Total	2015-38	2015-39	2015-40	2015-41	2015-42	2015-43	2015-44	2015-45	2015-46	2015-47	2015-48	2015-49	2015-50	2015-51	2015-52	2015-53	2016-1	2016-2	2016-3	2016-4	2016-5	2016-6	2016-7	2016-8
Planned in Week	2015-37	2705	2793	2646	2891	2588	3340	3023	3074	3283	2850	2248	1866	2649	1712										
	2015-38		2606	2041	2479	3340	3028	3064	3033	2674	3229	2708	1885	2611	2056	1319									
	2015-39			2783	1924	3090	3340	2250	3340	3078	3093	2245	2016	3114	1750	1269	435								
	2015-40				2225	2422	3340	2255	3104	3078	3340	2269	1836	3088	2163	1319	870	728							
	2015-41					2554	2660	2670	3066	3119	3124	2269	2225	2597	2006	1398	435	1594	2304						
	2015-42						0	0	0	0	0	0	0	0	0	0	0	0	0	0					
	2015-43							2628	2665	3117	2648	2636	1824	3061	1711	1405	435	2247	2267	1933	3332				
	2015-44								2840	2663	3340	2228	1992	2684	1844	1455	435	2379	2299	2173	3140	2297			
	2015-45									2793	2515	2238	2074	2659	2859	1131	550	1816	1924	2840	3340	2125	2484		
	2015-46										3036	1762	2268	2659	2732	1225	755	1828	2444	2424	3320	2215	2153	3097	
	2015-47											2648	2076	2518	2698	625	1239	1828	2161	3067	3021	2227	3092	2680	3268

Appendix H. Capacity Scenarios

Table 34: Kuga-Mondeo possible capacity scenarios

	Audit Booth		EOL		Frame Station		Assembly Line			Ouput	FTE	Output/FT
	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j		p^i,j(a^i,j)	w^tot	
Kuga-Mondeo	1	211	1	117	1	69	3	84		69	10	6,90
Kuga-Mondeo	1	211	1	117	1	69	4	112		69	11	6,27
Kuga-Mondeo	1	211	1	117	1	69	5	140		69	12	5,75
Kuga-Mondeo	1	211	1	117	1	69	6	168		69	13	5,31
Kuga-Mondeo	1	211	1	117	1	69	7	196		69	14	4,93
Kuga-Mondeo	1	211	1	117	1	69	8	224		69	15	4,60
Kuga-Mondeo	1	211	1	117	2	138	3	84		84	11	7,64
Kuga-Mondeo	1	211	1	117	2	138	4	112		112	12	9,33
Kuga-Mondeo	1	211	1	117	2	138	5	140		117	13	9,00
Kuga-Mondeo	1	211	1	117	2	138	6	168		117	14	8,36
Kuga-Mondeo	1	211	1	117	2	138	7	196		117	15	7,80
Kuga-Mondeo	1	211	1	117	2	138	8	224		117	16	7,31
Kuga-Mondeo	1	211	1	117	3	207	3	84		84	12	7,00
Kuga-Mondeo	1	211	1	117	3	207	4	112		112	13	8,62
Kuga-Mondeo	1	211	1	117	3	207	5	140		117	14	8,36
Kuga-Mondeo	1	211	1	117	3	207	6	168		117	15	7,80
Kuga-Mondeo	1	211	1	117	3	207	7	196		117	16	7,31
Kuga-Mondeo	1	211	1	117	3	207	8	224		117	17	6,88
Kuga-Mondeo	1	211	2	234	1	69	3	84		69	11	6,27
Kuga-Mondeo	1	211	2	234	1	69	4	112		69	12	5,75
Kuga-Mondeo	1	211	2	234	1	69	5	140		69	13	5,31
Kuga-Mondeo	1	211	2	234	1	69	6	168		69	14	4,93
Kuga-Mondeo	1	211	2	234	1	69	7	196		69	15	4,60
Kuga-Mondeo	1	211	2	234	1	69	8	224		69	16	4,31
Kuga-Mondeo	1	211	2	234	2	138	3	84		84	12	7,00
Kuga-Mondeo	1	211	2	234	2	138	4	112		112	13	8,62
Kuga-Mondeo	1	211	2	234	2	138	5	140		138	14	9,86
Kuga-Mondeo	1	211	2	234	2	138	6	168		138	15	9,20
Kuga-Mondeo	1	211	2	234	2	138	7	196		138	16	8,63
Kuga-Mondeo	1	211	2	234	2	138	8	224		138	17	8,12
Kuga-Mondeo	1	211	2	234	3	207	3	84		84	13	6,46
Kuga-Mondeo	1	211	2	234	3	207	4	112		112	14	8,00
Kuga-Mondeo	1	211	2	234	3	207	5	140		140	15	9,33
Kuga-Mondeo	1	211	2	234	3	207	6	168		168	16	10,50
Kuga-Mondeo	1	211	2	234	3	207	7	196		196	17	11,53
Kuga-Mondeo	1	211	2	234	3	207	8	224		207	18	11,50
Kuga-Mondeo	1	211	3	351	1	69	3	84		69	12	5,75
Kuga-Mondeo	1	211	3	351	1	69	4	112		69	13	5,31
Kuga-Mondeo	1	211	3	351	1	69	5	140		69	14	4,93
Kuga-Mondeo	1	211	3	351	1	69	6	168		69	15	4,60
Kuga-Mondeo	1	211	3	351	1	69	7	196		69	16	4,31
Kuga-Mondeo	1	211	3	351	1	69	8	224		69	17	4,06
Kuga-Mondeo	1	211	3	351	2	138	3	84		84	13	6,46
Kuga-Mondeo	1	211	3	351	2	138	4	112		112	14	8,00
Kuga-Mondeo	1	211	3	351	2	138	5	140		138	15	9,20
Kuga-Mondeo	1	211	3	351	2	138	6	168		138	16	8,63
Kuga-Mondeo	1	211	3	351	2	138	7	196		138	17	8,12
Kuga-Mondeo	1	211	3	351	2	138	8	224		138	18	7,67
Kuga-Mondeo	1	211	3	351	3	207	3	84		84	14	6,00
Kuga-Mondeo	1	211	3	351	3	207	4	112		112	15	7,47
Kuga-Mondeo	1	211	3	351	3	207	5	140		140	16	8,75
Kuga-Mondeo	1	211	3	351	3	207	6	168		168	17	9,88
Kuga-Mondeo	1	211	3	351	3	207	7	196		196	18	10,89
Kuga-Mondeo	1	211	3	351	3	207	8	224		207	19	10,89

	Audit Booth		EOL		Frame Station		Assembly Line			Ouput	FTE	Output/FT
	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j		p^i,j(a^i,j	w^tot	
Kuga-Mondeo	2	422	1	117	1	69	3	84		69	11	6,27
Kuga-Mondeo	2	422	1	117	1	69	4	112		69	12	5,75
Kuga-Mondeo	2	422	1	117	1	69	5	140		69	13	5,31
Kuga-Mondeo	2	422	1	117	1	69	6	168		69	14	4,93
Kuga-Mondeo	2	422	1	117	1	69	7	196		69	15	4,60
Kuga-Mondeo	2	422	1	117	1	69	8	224		69	16	4,31
Kuga-Mondeo	2	422	1	117	2	138	3	84		84	12	7,00
Kuga-Mondeo	2	422	1	117	2	138	4	112		112	13	8,62
Kuga-Mondeo	2	422	1	117	2	138	5	140		117	14	8,36
Kuga-Mondeo	2	422	1	117	2	138	6	168		117	15	7,80
Kuga-Mondeo	2	422	1	117	2	138	7	196		117	16	7,31
Kuga-Mondeo	2	422	1	117	2	138	8	224		117	17	6,88
Kuga-Mondeo	2	422	1	117	3	207	3	84		84	13	6,46
Kuga-Mondeo	2	422	1	117	3	207	4	112		112	14	8,00
Kuga-Mondeo	2	422	1	117	3	207	5	140		117	15	7,80
Kuga-Mondeo	2	422	1	117	3	207	6	168		117	16	7,31
Kuga-Mondeo	2	422	1	117	3	207	7	196		117	17	6,88
Kuga-Mondeo	2	422	1	117	3	207	8	224		117	18	6,50
Kuga-Mondeo	2	422	2	234	1	69	3	84		69	12	5,75
Kuga-Mondeo	2	422	2	234	1	69	4	112		69	13	5,31
Kuga-Mondeo	2	422	2	234	1	69	5	140		69	14	4,93
Kuga-Mondeo	2	422	2	234	1	69	6	168		69	15	4,60
Kuga-Mondeo	2	422	2	234	1	69	7	196		69	16	4,31
Kuga-Mondeo	2	422	2	234	1	69	8	224		69	17	4,06
Kuga-Mondeo	2	422	2	234	2	138	3	84		84	13	6,46
Kuga-Mondeo	2	422	2	234	2	138	4	112		112	14	8,00
Kuga-Mondeo	2	422	2	234	2	138	5	140		138	15	9,20
Kuga-Mondeo	2	422	2	234	2	138	6	168		138	16	8,63
Kuga-Mondeo	2	422	2	234	2	138	7	196		138	17	8,12
Kuga-Mondeo	2	422	2	234	2	138	8	224		138	18	7,67
Kuga-Mondeo	2	422	2	234	3	207	3	84		84	14	6,00
Kuga-Mondeo	2	422	2	234	3	207	4	112		112	15	7,47
Kuga-Mondeo	2	422	2	234	3	207	5	140		140	16	8,75
Kuga-Mondeo	2	422	2	234	3	207	6	168		168	17	9,88
Kuga-Mondeo	2	422	2	234	3	207	7	196		196	18	10,89
Kuga-Mondeo	2	422	2	234	3	207	8	224		207	19	10,89
Kuga-Mondeo	2	422	3	351	1	69	3	84		69	13	5,31
Kuga-Mondeo	2	422	3	351	1	69	4	112		69	14	4,93
Kuga-Mondeo	2	422	3	351	1	69	5	140		69	15	4,60
Kuga-Mondeo	2	422	3	351	1	69	6	168		69	16	4,31
Kuga-Mondeo	2	422	3	351	1	69	7	196		69	17	4,06
Kuga-Mondeo	2	422	3	351	1	69	8	224		69	18	3,83
Kuga-Mondeo	2	422	3	351	2	138	3	84		84	14	6,00
Kuga-Mondeo	2	422	3	351	2	138	4	112		112	15	7,47
Kuga-Mondeo	2	422	3	351	2	138	5	140		138	16	8,63
Kuga-Mondeo	2	422	3	351	2	138	6	168		138	17	8,12
Kuga-Mondeo	2	422	3	351	2	138	7	196		138	18	7,67
Kuga-Mondeo	2	422	3	351	2	138	8	224		138	19	7,26
Kuga-Mondeo	2	422	3	351	3	207	3	84		84	15	5,60
Kuga-Mondeo	2	422	3	351	3	207	4	112		112	16	7,00
Kuga-Mondeo	2	422	3	351	3	207	5	140		140	17	8,24
Kuga-Mondeo	2	422	3	351	3	207	6	168		168	18	9,33
Kuga-Mondeo	2	422	3	351	3	207	7	196		196	19	10,32
Kuga-Mondeo	2	422	3	351	3	207	8	224		207	20	10,35

Table 35: Possible XC60 capacity scenarios

	Audit Booth		EOL		Frame Station		Assembly Line			Ouput	FTE	Output/FT
	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j		p^i,j(a^i,j)	w^tot	
XC60	1	230	1	122	3	132	3	96		96	12	8,00
XC60	1	230	1	122	3	132	4	128		122	13	9,38
XC60	1	230	1	122	3	132	5	160		122	14	8,71
XC60	1	230	1	122	3	132	6	192		122	15	8,13
XC60	1	230	1	122	3	132	7	224		122	16	7,63
XC60	1	230	1	122	3	132	8	256		122	17	7,18
XC60	1	230	1	122	3	132	9	288		122	18	6,78
XC60	1	230	1	122	4	176	3	96		96	13	7,38
XC60	1	230	1	122	4	176	4	128		122	14	8,71
XC60	1	230	1	122	4	176	5	160		122	15	8,13
XC60	1	230	1	122	4	176	6	192		122	16	7,63
XC60	1	230	1	122	4	176	7	224		122	17	7,18
XC60	1	230	1	122	4	176	8	256		122	18	6,78
XC60	1	230	1	122	4	176	9	288		122	19	6,42
XC60	1	230	1	122	5	220	3	96		96	14	6,86
XC60	1	230	1	122	5	220	4	128		122	15	8,13
XC60	1	230	1	122	5	220	5	160		122	16	7,63
XC60	1	230	1	122	5	220	6	192		122	17	7,18
XC60	1	230	1	122	5	220	7	224		122	18	6,78
XC60	1	230	1	122	5	220	8	256		122	19	6,42
XC60	1	230	1	122	5	220	9	288		122	20	6,10
XC60	1	230	1	122	6	264	3	96		96	15	6,40
XC60	1	230	1	122	6	264	4	128		122	16	7,63
XC60	1	230	1	122	6	264	5	160		122	17	7,18
XC60	1	230	1	122	6	264	6	192		122	18	6,78
XC60	1	230	1	122	6	264	7	224		122	19	6,42
XC60	1	230	1	122	6	264	8	256		122	20	6,10
XC60	1	230	1	122	6	264	9	288		122	21	5,81
XC60	1	230	2	244	3	132	3	96		96	13	7,38
XC60	1	230	2	244	3	132	4	128		128	14	9,14
XC60	1	230	2	244	3	132	5	160		132	15	8,80
XC60	1	230	2	244	3	132	6	192		132	16	8,25
XC60	1	230	2	244	3	132	7	224		132	17	7,76
XC60	1	230	2	244	3	132	8	256		132	18	7,33
XC60	1	230	2	244	3	132	9	288		132	19	6,95
XC60	1	230	2	244	4	176	3	96		96	14	6,86
XC60	1	230	2	244	4	176	4	128		128	15	8,53
XC60	1	230	2	244	4	176	5	160		160	16	10,00
XC60	1	230	2	244	4	176	6	192		176	17	10,35
XC60	1	230	2	244	4	176	7	224		176	18	9,78
XC60	1	230	2	244	4	176	8	256		176	19	9,26
XC60	1	230	2	244	4	176	9	288		176	20	8,80
XC60	1	230	2	244	5	220	3	96		96	15	6,40
XC60	1	230	2	244	5	220	4	128		128	16	8,00
XC60	1	230	2	244	5	220	5	160		160	17	9,41
XC60	1	230	2	244	5	220	6	192		192	18	10,67
XC60	1	230	2	244	5	220	7	224		220	19	11,58
XC60	1	230	2	244	5	220	8	256		220	20	11,00
XC60	1	230	2	244	5	220	9	288		220	21	10,48
XC60	1	230	2	244	6	264	3	96		96	16	6,00
XC60	1	230	2	244	6	264	4	128		128	17	7,53
XC60	1	230	2	244	6	264	5	160		160	18	8,89
XC60	1	230	2	244	6	264	6	192		192	19	10,11
XC60	1	230	2	244	6	264	7	224		224	20	11,20
XC60	1	230	2	244	6	264	8	256		230	21	10,95
XC60	1	230	2	244	6	264	9	288		230	22	10,45
XC60	1	230	3	366	3	132	3	96		96	14	6,86
XC60	1	230	3	366	3	132	4	128		128	15	8,53
XC60	1	230	3	366	3	132	5	160		132	16	8,25
XC60	1	230	3	366	3	132	6	192		132	17	7,76
XC60	1	230	3	366	3	132	7	224		132	18	7,33
XC60	1	230	3	366	3	132	8	256		132	19	6,95
XC60	1	230	3	366	3	132	9	288		132	20	6,60
XC60	1	230	3	366	4	176	3	96		96	15	6,40
XC60	1	230	3	366	4	176	4	128		128	16	8,00
XC60	1	230	3	366	4	176	5	160		160	17	9,41
XC60	1	230	3	366	4	176	6	192		176	18	9,78
XC60	1	230	3	366	4	176	7	224		176	19	9,26
XC60	1	230	3	366	4	176	8	256		176	20	8,80
XC60	1	230	3	366	4	176	9	288		176	21	8,38
XC60	1	230	3	366	5	220	3	96		96	16	6,00
XC60	1	230	3	366	5	220	4	128		128	17	7,53
XC60	1	230	3	366	5	220	5	160		160	18	8,89
XC60	1	230	3	366	5	220	6	192		192	19	10,11
XC60	1	230	3	366	5	220	7	224		220	20	11,00
XC60	1	230	3	366	5	220	8	256		220	21	10,48
XC60	1	230	3	366	5	220	9	288		220	22	10,00
XC60	1	230	3	366	6	264	3	96		96	17	5,65
XC60	1	230	3	366	6	264	4	128		128	18	7,11
XC60	1	230	3	366	6	264	5	160		160	19	8,42
XC60	1	230	3	366	6	264	6	192		192	20	9,60
XC60	1	230	3	366	6	264	7	224		224	21	10,67
XC60	1	230	3	366	6	264	8	256		230	22	10,45
XC60	1	230	3	366	6	264	9	288		230	23	10,00

	Audit Booth		EOL		Frame Station		Assembly Line					
	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j	a^i,j	p^i,j		p^i,j(a^i,j)	w^tot	
XC60	2	460	1	122	3	132	3	96		96	13	7,38
XC60	2	460	1	122	3	132	4	128		122	14	8,71
XC60	2	460	1	122	3	132	5	160		122	15	8,13
XC60	2	460	1	122	3	132	6	192		122	16	7,63
XC60	2	460	1	122	3	132	7	224		122	17	7,18
XC60	2	460	1	122	3	132	8	256		122	18	6,78
XC60	2	460	1	122	3	132	9	288		122	19	6,42
XC60	2	460	1	122	4	176	3	96		96	14	6,86
XC60	2	460	1	122	4	176	4	128		122	15	8,13
XC60	2	460	1	122	4	176	5	160		122	16	7,63
XC60	2	460	1	122	4	176	6	192		122	17	7,18
XC60	2	460	1	122	4	176	7	224		122	18	6,78
XC60	2	460	1	122	4	176	8	256		122	19	6,42
XC60	2	460	1	122	4	176	9	288		122	20	6,10
XC60	2	460	1	122	5	220	3	96		96	15	6,40
XC60	2	460	1	122	5	220	4	128		122	16	7,63
XC60	2	460	1	122	5	220	5	160		122	17	7,18
XC60	2	460	1	122	5	220	6	192		122	18	6,78
XC60	2	460	1	122	5	220	7	224		122	19	6,42
XC60	2	460	1	122	5	220	8	256		122	20	6,10
XC60	2	460	1	122	5	220	9	288		122	21	5,81
XC60	2	460	1	122	6	264	3	96		96	16	6,00
XC60	2	460	1	122	6	264	4	128		122	17	7,18
XC60	2	460	1	122	6	264	5	160		122	18	6,78
XC60	2	460	1	122	6	264	6	192		122	19	6,42
XC60	2	460	1	122	6	264	7	224		122	20	6,10
XC60	2	460	1	122	6	264	8	256		122	21	5,81
XC60	2	460	1	122	6	264	9	288		122	22	5,55
XC60	2	460	2	244	3	132	3	96		96	14	6,86
XC60	2	460	2	244	3	132	4	128		128	15	8,53
XC60	2	460	2	244	3	132	5	160		132	16	8,25
XC60	2	460	2	244	3	132	6	192		132	17	7,76
XC60	2	460	2	244	3	132	7	224		132	18	7,33
XC60	2	460	2	244	3	132	8	256		132	19	6,95
XC60	2	460	2	244	3	132	9	288		132	20	6,60
XC60	2	460	2	244	4	176	3	96		96	15	6,40
XC60	2	460	2	244	4	176	4	128		128	16	8,00
XC60	2	460	2	244	4	176	5	160		160	17	9,41
XC60	2	460	2	244	4	176	6	192		176	18	9,78
XC60	2	460	2	244	4	176	7	224		176	19	9,26
XC60	2	460	2	244	4	176	8	256		176	20	8,80
XC60	2	460	2	244	4	176	9	288		176	21	8,38
XC60	2	460	2	244	5	220	3	96		96	16	6,00
XC60	2	460	2	244	5	220	4	128		128	17	7,53
XC60	2	460	2	244	5	220	5	160		160	18	8,89
XC60	2	460	2	244	5	220	6	192		192	19	10,11
XC60	2	460	2	244	5	220	7	224		220	20	11,00
XC60	2	460	2	244	5	220	8	256		220	21	10,48
XC60	2	460	2	244	5	220	9	288		220	22	10,00
XC60	2	460	2	244	6	264	3	96		96	17	5,65
XC60	2	460	2	244	6	264	4	128		128	18	7,11
XC60	2	460	2	244	6	264	5	160		160	19	8,42
XC60	2	460	2	244	6	264	6	192		192	20	9,60
XC60	2	460	2	244	6	264	7	224		224	21	10,67
XC60	2	460	2	244	6	264	8	256		244	22	11,09
XC60	2	460	2	244	6	264	9	288		244	23	10,61
XC60	2	460	3	366	3	132	3	96		96	15	6,40
XC60	2	460	3	366	3	132	4	128		128	16	8,00
XC60	2	460	3	366	3	132	5	160		132	17	7,76
XC60	2	460	3	366	3	132	6	192		132	18	7,33
XC60	2	460	3	366	3	132	7	224		132	19	6,95
XC60	2	460	3	366	3	132	8	256		132	20	6,60
XC60	2	460	3	366	3	132	9	288		132	21	6,29
XC60	2	460	3	366	4	176	3	96		96	16	6,00
XC60	2	460	3	366	4	176	4	128		128	17	7,53
XC60	2	460	3	366	4	176	5	160		160	18	8,89
XC60	2	460	3	366	4	176	6	192		176	19	9,26
XC60	2	460	3	366	4	176	7	224		176	20	8,80
XC60	2	460	3	366	4	176	8	256		176	21	8,38
XC60	2	460	3	366	4	176	9	288		176	22	8,00
XC60	2	460	3	366	5	220	3	96		96	17	5,65
XC60	2	460	3	366	5	220	4	128		128	18	7,11
XC60	2	460	3	366	5	220	5	160		160	19	8,42
XC60	2	460	3	366	5	220	6	192		192	20	9,60
XC60	2	460	3	366	5	220	7	224		220	21	10,48
XC60	2	460	3	366	5	220	8	256		220	22	10,00
XC60	2	460	3	366	5	220	9	288		220	23	9,57
XC60	2	460	3	366	6	264	3	96		96	18	5,33
XC60	2	460	3	366	6	264	4	128		128	19	6,74
XC60	2	460	3	366	6	264	5	160		160	20	8,00
XC60	2	460	3	366	6	264	6	192		192	21	9,14
XC60	2	460	3	366	6	264	7	224		224	22	10,18
XC60	2	460	3	366	6	264	8	256		256	23	11,13
XC60	2	460	3	366	6	264	9	288		264	24	11,00

Appendix I. Calculation of Safety Stocks

First, the desired service level $\boldsymbol{\alpha}$ is required to estimate the height of the safety stock. This service level is based on the ratio between holding costs $\boldsymbol{C^S}$ and backorder costs $\boldsymbol{C^B}$, retrieved from classic newsvendor theory (Silver et al., 1998);

$$z_\alpha = \left(\frac{C^B}{C^S + C^B}\right)$$

The holding costs are estimated to be 26,77% per year and thus the costs of holding an item in inventory per period (week) are the following:

$$C^S = \frac{item\ variable\ cost \times holding\ costs}{52\ weeks}$$

Since an XC60 roof systems has an item variable costs of €256.85 and a Kuga-Mondeo roof system's variable costs is €253.16, the costs for carrying one XC60 roof system are €1.23 per period. Hence, the cost for having one Kuga-Mondeo roof in stock is €1.22.

The cost for having one item in backorder are estimated by calculating the average cost per emergency shipment, since this was the only data available. The estimation of average backorder costs (€19.73) is given below in Table 36:

Table 36: Estimation of backorder costs

	Emergency Shipments	
# of Roofs	**Total Costs Shipment**	**Cost per Roof**
24	€ 1.150	€ 48
24	€ 1.150	€ 48
156	€ 2.395	€ 15
216	€ 1.677	€ 8
216	€ 2.495	€ 12
216	€ 2.495	€ 12
144	€ 2.570	€ 18
48	€ 1.470	€ 31
144	€ 2.495	€ 17
144	€ 2.495	€ 17
204	€ 2.495	€ 12
144	€ 2.395	€ 17
120	€ 2.395	€ 20
92	€ 2.395	€ 26
96	€ 2.395	€ 25
192	€ 2.395	€ 12
192	€ 2.395	€ 12
192	€ 2.395	€ 12
192	€ 2.395	€ 12
Backorder costs per Roof		**€ 19,73**

This results in the following desired service levels:

$$(XC60)z_\alpha = \left(\frac{€19.73}{€1.23 + €19.73}\right) = 94.11\%$$

$$(Kuga - Mondeo)z_\alpha = \left(\frac{€19.73}{€1.22 + €19.73}\right) = 94.19\%$$

For convenience, the service levels for both finished goods are set on 95%. This results in a z-value of approximately 1.65 and thus the calculation of safety stocks are the following (King, 2011):

$$Safety\ Stock = z_\alpha \times \sqrt{{PLT}/{t}} \times \sigma_t^D = 1.65 \times \sqrt{{PLT}/{t}} \times \sigma_t^D$$

The planning lead time $\boldsymbol{PLT}$ is used to estimate the time that the safety stock need to cover. The period length $\boldsymbol{t}$ is used to correct for pooling of variance. Lastly, the standard deviation is used to be able to estimate the safety stock level. This calculation is solely based on demand uncertainty. A more extensive calculation can be made for the incorporation of variability in lead time. However, we use it as a measure to cover order variability over time. Customers are allowed to expedite an order by two days. To cover this phenomena the following model is used (King, 2011):

$$Safety\ Stock = \left(z_\alpha \times \sqrt{{PLT}/{t}} \times \sigma_t^D\right) + (z_\alpha \times \sigma^{PLT} \times \mu_T^D)$$

Here, the standard deviation of the planning lead time $\boldsymbol{\sigma^{PLT}}$ is set on 2 days. This way the safety stock is always able to cover for short-term order expediting. The average demand over the planning horizon $\boldsymbol{\mu_t^D}$ is used to estimate the height of the additional safety buffer.

Appendix J. Holding Cost Calculation

The holding costs for IRS are calculated using the model of Azzi et al. (2014). The calculated costs are given below.

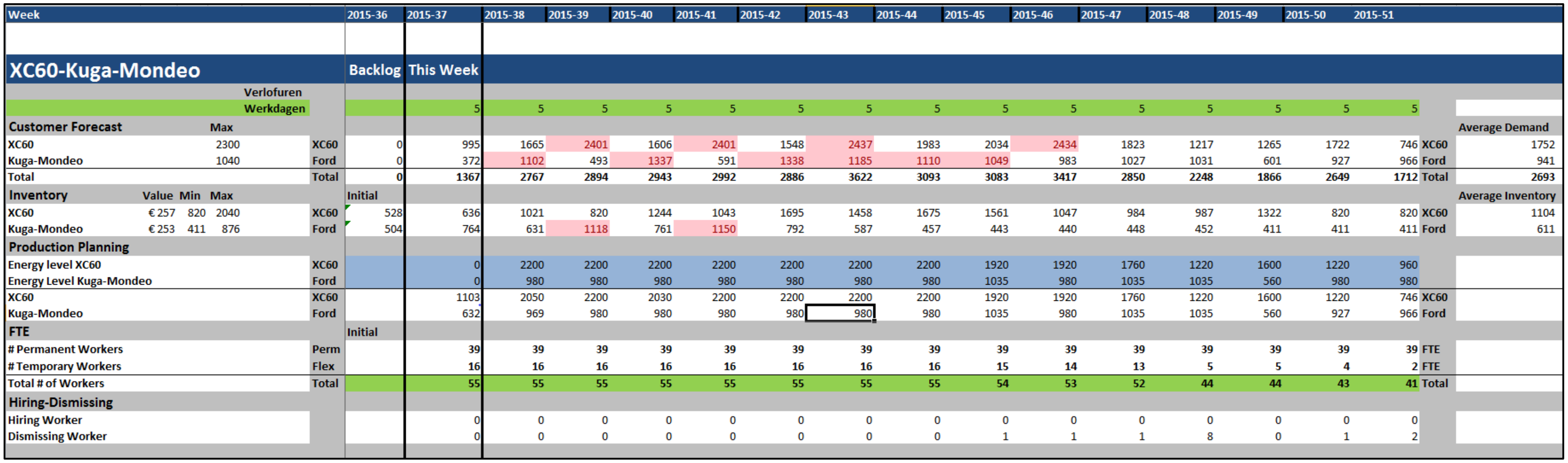
Table 37: Estimation of inventory holding costs for IRS

Average inventory on hand per year	€ 12.810.880,00	
Evident costs Investment costs	**Actual costs**	**Percentage**
1. Floor space	€ 426.704,40	3,33%
2. Energy	€ 65.214,24	0,51%
3. Cleaning	€ 26.752,70	0,21%
4. Surveillance	€ 11.000,00	0,09%
5. Insurances	€ 36.417,20	0,28%
6. Taxes	NA	0,00%
7. Material handling/storage equipments	€ 190.200,00	1,48%
8. WHMS and HAS equipments	€ 1.245,00	0,01%
9. Maintenance	€ 8.000,00	0,06%
10. Direct labor	€ 260.147,09	2,03%
Semi-evident costs		
1. Obsolescence	€ 392.000,00	3,06%
2. Product damage	NA	0,00%
3. Product depreciation	€ 468.000,00	3,65%
4. Product deterioration/expiration	NA	0,00%
5. Indirect labor and supervision	€ 349.703,73	2,73%
6. Stock list execution	€ 11.000,00	0,09%
Hidden costs		
1. Inspection and counting during the year	€ 15.600,00	0,12%
2. Remanufacturing	NA	0,00%
3. Repackaging and relabelling	NA	0,00%
4. Lost sales or backlog	NA	0,00%
Annual opportunity costs	€ 1.281.088,00	10,00%
Total Inventory Carying costs (2015)		**27,66%**

Appendix K. IRS Planning Tool

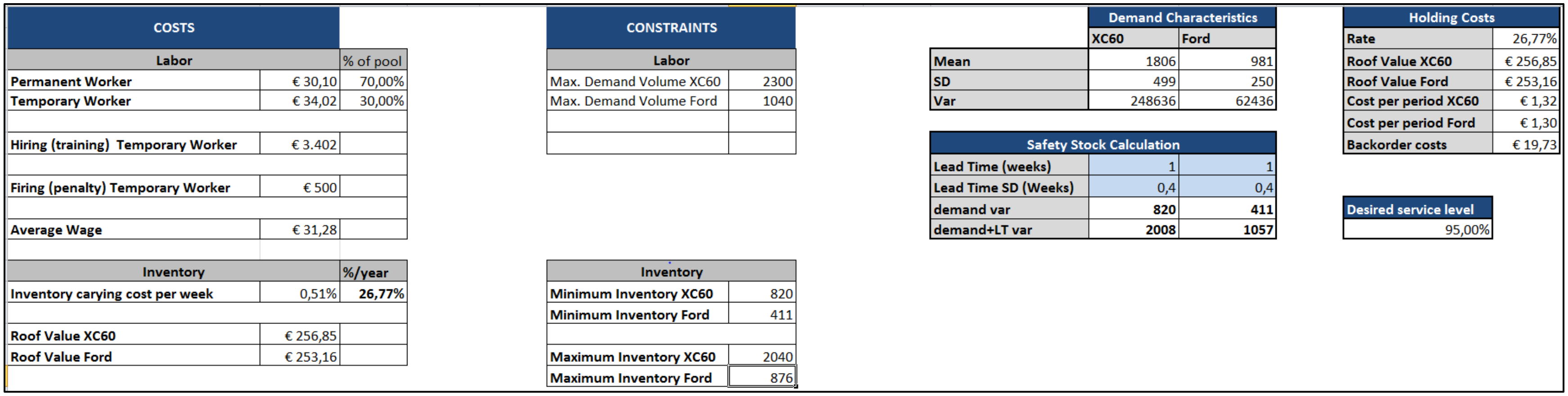
In this appendix the user interfaces of the planning tool are included. In Figure 20 the management interface is shown that presents information about the production planning, customer demands, inventory statuses and required workforce, for each period. Next, the input screen is presented in Figure 21, in which the input parameters of the IRS model can be changed. Lasts, the input screen for the capacity levels is presented in Figure 22.

The model uses the existing data sheets to fill the model with information about; customer forecasts, current inventory status, planned orders from the previously scheduled MPS and the available workforce. This data is retrieved from the ERP via cyber queries that make data dumps that can be used in MS Excel. This is in alignment with the current working methods of the planning department at IRS.



Week					2015-36	2015-37	2015-38	2015-39	2015-40	2015-41	2015-42	2015-43	2015-44	2015-45	2015-46	2015-47	2015-48	2015-49	2015-50	2015-51		
XC60-Kuga-Mondeo					**Backlog**	**This Week**																
Verlofuren																						
Werkdagen						5	5	5	5	5	5	5	5	5	5	5	5	5	5	5		
Customer Forecast			**Max**																			**Average Demand**
XC60			2300	**XC60**	0	995	1665	2401	1606	2401	1548	2437	1983	2034	2434	1823	1217	1265	1722	746	**XC60**	1752
Kuga-Mondeo			1040	**Ford**	0	372	1102	493	1337	591	1338	1185	1110	1049	983	1027	1031	601	927	966	**Ford**	941
Total				**Total**	**0**	**1367**	**2767**	**2894**	**2943**	**2992**	**2886**	**3622**	**3093**	**3083**	**3417**	**2850**	**2248**	**1866**	**2649**	**1712**	**Total**	**2693**
Inventory	**Value**	**Min**	**Max**		**Initial**																	**Average Inventory**
XC60	€ 257	820	2040	**XC60**	528	636	1021	820	1244	1043	1695	1458	1675	1561	1047	984	987	1322	820	820	**XC60**	1104
Kuga-Mondeo	€ 253	411	876	**Ford**	504	764	631	1118	761	1150	792	587	457	443	440	448	452	411	411	411	**Ford**	611
Production Planning																						
Energy level XC60				**XC60**		0	2200	2200	2200	2200	2200	2200	2200	1920	1920	1760	1220	1600	1220	960		
Energy Level Kuga-Mondeo				**Ford**		0	980	980	980	980	980	980	980	1035	980	1035	1035	560	980	980		
XC60				**XC60**		1103	2050	2200	2030	2200	2200	2200	2200	1920	1920	1760	1220	1600	1220	746	**XC60**	
Kuga-Mondeo				**Ford**		632	969	980	980	980	980	980	980	1035	980	1035	1035	560	927	966	**Ford**	
FTE					**Initial**																	
# Permanent Workers				**Perm**		**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**39**	**FTE**	
# Temporary Workers				**Flex**		**16**	**16**	**16**	**16**	**16**	**16**	**16**	**16**	**15**	**14**	**13**	**5**	**5**	**4**	**2**	**FTE**	
Total # of Workers				**Total**		**55**	**55**	**55**	**55**	**55**	**55**	**55**	**55**	**54**	**53**	**52**	**44**	**44**	**43**	**41**	**Total**	
Hiring-Dismissing																						
Hiring Worker						0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Dismissing Worker						0	0	0	0	0	0	0	0	1	1	1	8	0	1	2		

Figure 20: Management interface presenting customer forecasts, inventory status, planned orders, and required workforce size



COSTS		
Labor		% of pool
Permanent Worker	€ 30,10	70,00%
Temporary Worker	€ 34,02	30,00%
Hiring (training) Temporary Worker	€ 3.402	
Firing (penalty) Temporary Worker	€ 500	
Average Wage	€ 31,28	
Inventory		**%/year**
Inventory carying cost per week	0,51%	**26,77%**
Roof Value XC60	€ 256,85	
Roof Value Ford	€ 253,16	

CONSTRAINTS	
Labor	
Max. Demand Volume XC60	2300
Max. Demand Volume Ford	1040
Inventory	
Minimum Inventory XC60	820
Minimum Inventory Ford	411
Maximum Inventory XC60	2040
Maximum Inventory Ford	876

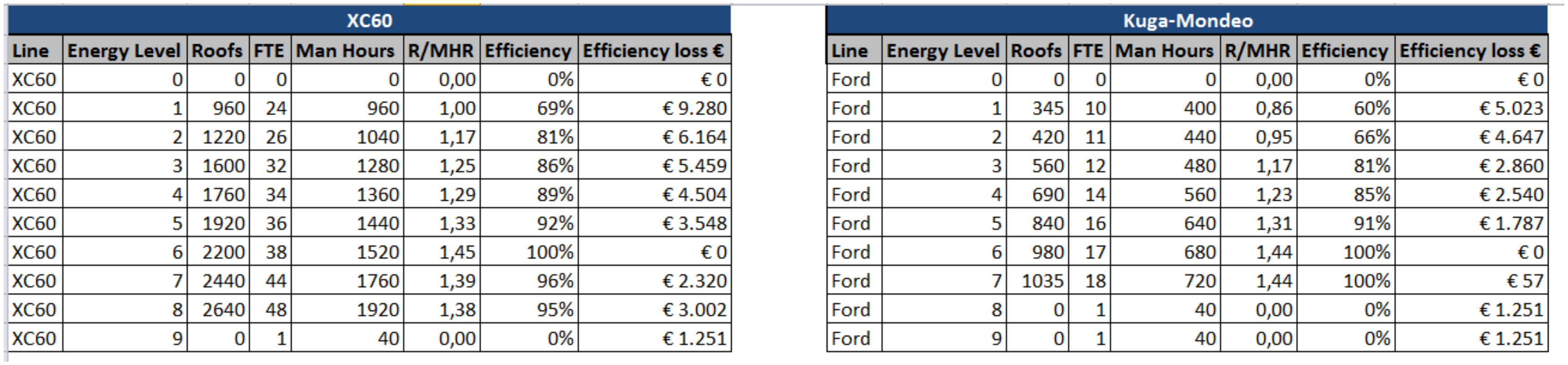
	Demand Characteristics	
	XC60	**Ford**
Mean	1806	981
SD	499	250
Var	248636	62436

Safety Stock Calculation		
Lead Time (weeks)	1	1
Lead Time SD (Weeks)	0,4	0,4
demand var	**820**	**411**
demand+LT var	**2008**	**1057**

Holding Costs	
Rate	26,77%
Roof Value XC60	€ 256,85
Roof Value Ford	€ 253,16
Cost per period XC60	€ 1,32
Cost per period Ford	€ 1,30
Backorder costs	€ 19,73

Desired service level
95,00%

Figure 21: Parameter input interface in which adjustments on the parameters for the model can be made



XC60							
Line	**Energy Level**	**Roofs**	**FTE**	**Man Hours**	**R/MHR**	**Efficiency**	**Efficiency loss €**
XC60	0	0	0	0	0,00	0%	€ 0
XC60	1	960	24	960	1,00	69%	€ 9.280
XC60	2	1220	26	1040	1,17	81%	€ 6.164
XC60	3	1600	32	1280	1,25	86%	€ 5.459
XC60	4	1760	34	1360	1,29	89%	€ 4.504
XC60	5	1920	36	1440	1,33	92%	€ 3.548
XC60	6	2200	38	1520	1,45	100%	€ 0
XC60	7	2440	44	1760	1,39	96%	€ 2.320
XC60	8	2640	48	1920	1,38	95%	€ 3.002
XC60	9	0	1	40	0,00	0%	€ 1.251

Kuga-Mondeo							
Line	**Energy Level**	**Roofs**	**FTE**	**Man Hours**	**R/MHR**	**Efficiency**	**Efficiency loss €**
Ford	0	0	0	0	0,00	0%	€ 0
Ford	1	345	10	400	0,86	60%	€ 5.023
Ford	2	420	11	440	0,95	66%	€ 4.647
Ford	3	560	12	480	1,17	81%	€ 2.860
Ford	4	690	14	560	1,23	85%	€ 2.540
Ford	5	840	16	640	1,31	91%	€ 1.787
Ford	6	980	17	680	1,44	100%	€ 0
Ford	7	1035	18	720	1,44	100%	€ 57
Ford	8	0	1	40	0,00	0%	€ 1.251
Ford	9	0	1	40	0,00	0%	€ 1.251

Figure 22: Capacity scenario input interface in which capacity scenarios can be altered

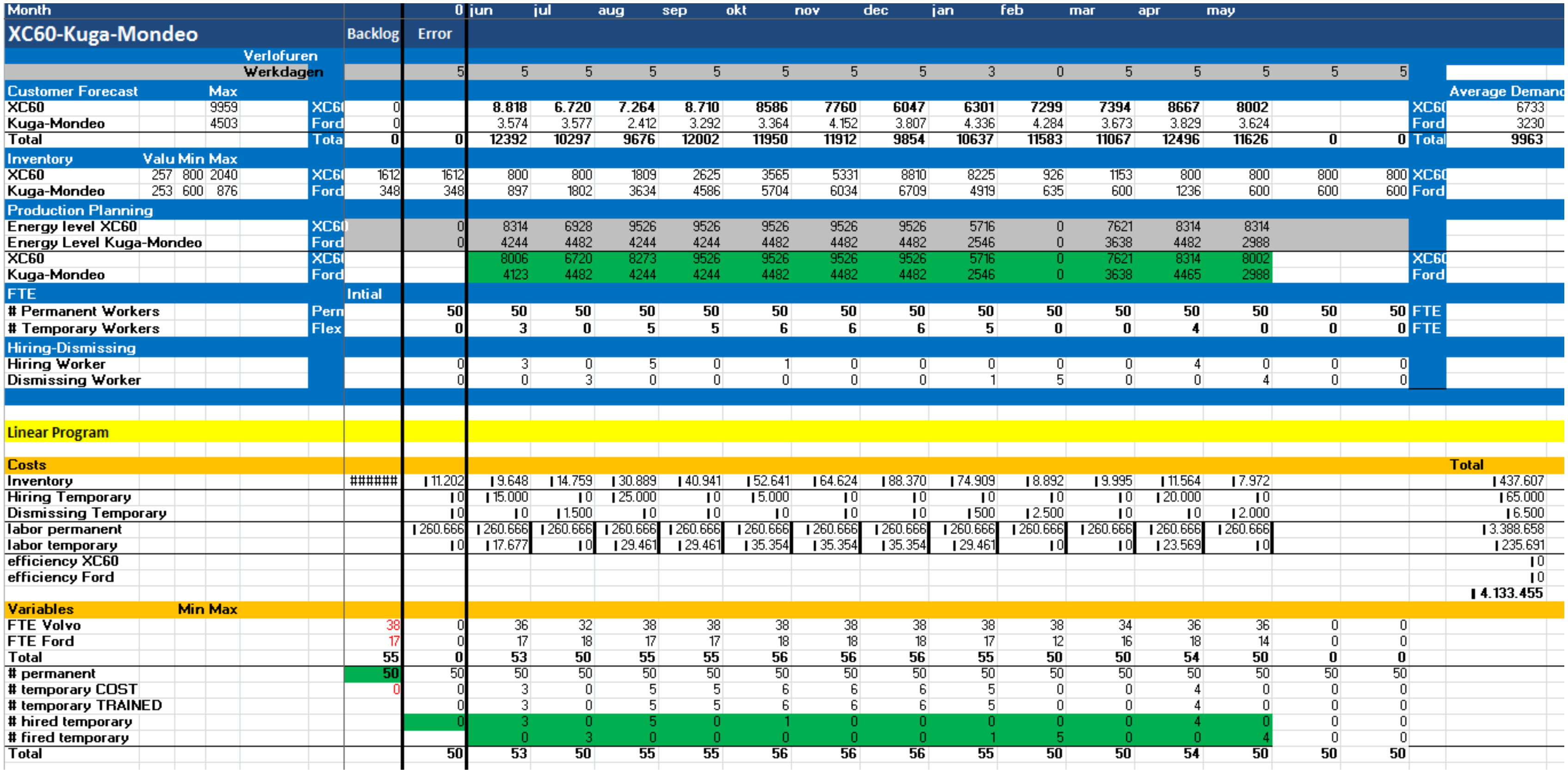
Appendix L. Estimation of Optimal Number of Permanent Employees

The total number of was estimated by allowing the model to use $\boldsymbol{w^p}$ as a **decision variable**. This means that the IRS model is used as presented in section 4.4, but with an additional decision variable and additional constraints. We allowed the model to compute the optimal ratio of permanent and contingent workers, by calculating the number of permanent worker once for all periods. This decision variable $\boldsymbol{w^p}$ is constrained by the fact that it has to be an integer that is equal or greater than 0;

$$\boldsymbol{w^p} \in \mathbb{N}$$

Furthermore, the number of period is changed to 12, since we used 12 months of demand forecasts. Consequently, the length of a period was increased to months, instead of weeks. All parameters were adjusted to months as well. We assumed that the length of a month was ${}^{52}/_{12} = 4\,{}^{1}/_{3}\,weeks$ for each month. Hence, all costs were increased by 4.33 and the capacity scenarios were multiplied by 4.33 as well. Lastly, we neglected training time in this model, and included the costs of a week of training in the hiring costs. We believed that the inclusion of the training period was irrelevant for the estimation of the ratio between permanent and contingent capacity. Training time would be 0.25 periods in this case, and the inclusion of training time is more relevant when actually hiring a person and need him trained on time, than when one is estimating the long-term composition of the workforce.

The computational model and results are included in Figure 23. The demand forecasts are included in the figure and are on average 6733 XC60 roof systems per month and 3230 Kuga-Mondeo roof systems per month. The optimal number of permanent workers is 50, and the maximum number of contingent workers that is hired in a period is 6.



Month						0	jun	jul	aug	sep	okt	nov	dec	jan	feb	mar	apr	may				
XC60-Kuga-Mondeo					Backlog	Error																
			Verlofuren																			
			Werkdagen			5	5	5	5	5	5	5	5	3	0	5	5	5	5	5		
Customer Forecast			Max																			Average Demand
XC60			9959	XC60	0		**8.818**	**6.720**	**7.264**	**8.710**	**8586**	**7760**	**6047**	**6301**	**7299**	**7394**	**8667**	**8002**			XC60	6733
Kuga-Mondeo			4503	Ford	0		3.574	3.577	2.412	3.292	3.364	4.152	3.807	4.336	4.284	3.673	3.829	3.624			Ford	3230
Total				Tota	**0**	**0**	**12392**	**10297**	**9676**	**12002**	**11950**	**11912**	**9854**	**10637**	**11583**	**11067**	**12496**	**11626**	**0**	**0**	Total	**9963**
Inventory	Valu	Min	Max																			
XC60	257	800	2040	XC60	1612	1612	800	800	1809	2625	3565	5331	8810	8225	926	1153	800	800	800	800	XC60	
Kuga-Mondeo	253	600	876	Ford	348	348	897	1802	3634	4586	5704	6034	6709	4919	635	600	1236	600	600	600	Ford	
Production Planning																						
Energy level XC60				XC60		0	8314	6928	9526	9526	9526	9526	9526	5716	0	7621	8314	8314				
Energy Level Kuga-Mondeo				Ford		0	4244	4482	4244	4244	4482	4482	4482	2546	0	3638	4482	2988				
XC60				XC60			8006	6720	8273	9526	9526	9526	9526	5716	0	7621	8314	8002			XC60	
Kuga-Mondeo				Ford			4123	4482	4244	4244	4482	4482	4482	2546	0	3638	4465	2988			Ford	
FTE					Intial																	
# Permanent Workers				Perm		**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	**50**	FTE	
# Temporary Workers				Flex		**0**	**3**	**0**	**5**	**5**	**6**	**6**	**6**	**5**	**0**	**0**	**4**	**0**	**0**	**0**	FTE	
Hiring-Dismissing																						
Hiring Worker						0	3	0	5	0	1	0	0	0	0	0	4	0	0	0		
Dismissing Worker						0	0	3	0	0	0	0	0	1	5	0	0	4	0	0		
Linear Program																						
Costs																						Total
Inventory					######	❙11.202	❙9.648	❙14.759	❙30.889	❙40.941	❙52.641	❙64.624	❙88.370	❙74.909	❙8.892	❙9.995	❙11.564	❙7.972				❙437.607
Hiring Temporary						❙0	❙15.000	❙0	❙25.000	❙0	❙5.000	❙0	❙0	❙0	❙0	❙0	❙20.000	❙0				❙65.000
Dismissing Temporary						❙0	❙0	❙1.500	❙0	❙0	❙0	❙0	❙0	❙500	❙2.500	❙0	❙0	❙2.000				❙6.500
labor permanent						❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666	❙260.666				❙3.388.658
labor temporary						❙0	❙17.677	❙0	❙29.461	❙29.461	❙35.354	❙35.354	❙35.354	❙29.461	❙0	❙0	❙23.569	❙0				❙235.691
efficiency XC60																						❙0
efficiency Ford																						❙0
																						❙4.133.455
Variables		Min	Max																			
FTE Volvo					38	0	36	32	38	38	38	38	38	38	38	34	36	36	0	0		
FTE Ford					17	0	17	18	17	17	18	18	18	17	12	16	18	14	0	0		
Total					**55**	**0**	**53**	**50**	**55**	**55**	**56**	**56**	**56**	**55**	**50**	**50**	**54**	**50**	**0**	**0**		
# permanent					**50**	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50		
# temporary COST					0	0	3	0	5	5	6	6	6	5	0	0	4	0	0	0		
# temporary TRAINED						0	3	0	5	5	6	6	6	5	0	0	4	0	0	0		
# hired temporary						0	3	0	5	0	1	0	0	0	0	0	4	0	0	0		
# fired temporary							0	3	0	0	0	0	0	1	5	0	0	4	0	0		
Total						**50**	**53**	**50**	**55**	**55**	**56**	**56**	**56**	**55**	**50**	**50**	**54**	**50**	**50**	**50**		

Figure 23: Computational model and results for the calculation of the ideal number of permanent employees in the system