MASTER

"Towards a Pearl Chain"

Vliegen, L.J.D.

Award date:
2021

MSc Graduate Thesis:

“Towards a Pearl Chain”

L. Vliegen – 1395807

3-8-2021

Technische Universiteit **Eindhoven** University of Technology

Supervisors:

dr. B. Aysolmaz	–	TU Eindhoven, IS
dr. ir. R. Dijkman	–	TU Eindhoven, IS
ir. A. van den Broeke	–	Truck Producer, Q&CI
ir. A. Tummers	–	Truck Producer, IT

Preface

This research is conducted as graduation assignment for the master Operations Management & Logistics at the TU Eindhoven. The choice for an internship company is optional and voluntary. With the help of the ESCF forum, I managed to get an internship at a certain truck producer which is called TP in the rest of this thesis report. TP is an established truck manufacturer with facilities all around the globe. The head office is based in the Netherlands and that is where I got to fulfil my assignment at the Quality & Continuous Improvement (Q&CI) department. The assignment "Towards a Pearl Chain" is drafted in collaboration with the IT department of TP. Because of the wide background of the assignment, I have got to work closely with people from both departments.

The scope of the project is to investigate the road towards a Pearl Chain model for TP. The Pearl Chain model uses a stable predefined order sequence. TP wants to know what is necessary to implement the Pearl Chain in their plants. Next to this, TP wants to know what can be gained in terms of money when the Pearl Chain is implemented. So the goal of this graduation research is to show the potential opportunities and the probable challenges of the Pearl Chain method for TP.

I would like to express my thanks to everyone who made the creation of this graduation thesis possible. Special thanks to my direct supervisors Ad van de Broeke from the Q&CI department and Annette Tummers from the IT department. Special thanks to Banu Aysolmaz and Remco Dijkman which were my direct supervisors from the TU Eindhoven. And a special thanks to Janco Spiekhout and Edwin van Walraven, the managers of the Q&CI and the IT department who sponsored the execution of the assignment. I would also like to express my thanks to all the employees from all the different departments within TP who helped me during my internship. I really liked working with everyone. I hope the developed research is considered as educational and relevant.

Thank you for your interest,

Luc Vliegen

Content

Executive Summary

This master graduation thesis is executed at TP in collaboration with the TU Eindhoven. The goal of the research is to investigate the road towards a Pearl Chain model for TP. The Pearl Chain method implicates that the production is based on a stable predefined order sequence. An important advantage of the Pearl Chain method is that components can be delivered Just-In-Sequence. The research investigates how to design a Pearl Chain model and what the potential opportunities and challenges are. The research is divided in a couple of phases. First, the problem is investigated by analysing the current situation. Then, a Pearl Chain model is designed and the method is evaluated with the help of a simulation model. At the end, conclusions and recommendations are drafted. A lot of scientific literature about Pearl Chain and Just-In-Sequence is found. However, the current literature is mostly focused on the car industry and not on the truck industry. Next to this, no quantitative evaluations in the production environment are found on this subject. These limitations are stated as the research gap for the current research.

The current production model at TP is analysed by interviewing stakeholders. After that, the processes are visualised. The supportive processes to realise a truck assembly are analysed and all the responsible departments are identified. Challenges in the current processes that prevent the implementation of a Pearl Chain are identified like the short frozen zone and the insecure production of the main components (axle set, engine & cabin). The primary production process is also analysed. In particular, the assembly process is within the scope of this research. Pearl Chain experts from Flexis, Nobleo and SAP are interviewed to gain more information on how to implement a Pearl Chain. The sequencing system, maintaining a stable sequence and controlling the material flow are some of the topics that are discussed. The new developed insights are applied on the current TP processes. From these new insights, a future state Pearl Chain model for TP is designed. The migration to SAP can be an opportunity to solve some of the current challenges.

To evaluate the potential benefits of a Pearl Chain model, a simulation is designed. With the help of data from the assembly plant, the current order sequence through the plant is replicated. The model is transformed into a stochastic model in order to use it for multiple purposes. One analysis focuses on the disturbances during the assembly while another analysis focuses on the amount of blockings before the assembly. The first analysis investigates the intermediate buffer occupation and the lead time. The second analysis investigates the amount of blockings in combination with various supply buffer sizes for the main components. The variable that is simulated is the order sequence within the plant and the supply sequence of the main components. The current state sequence is compared with randomly generated future state sequences. These future state sequences have a higher sequence stability. The future state results show that the intermediate buffer occupation and the lead time decreases and lower supply buffer sizes are needed to prevent most of the blockings. When reducing the buffer sizes, Up to €34,000 can be saved on the trucks in the intermediate buffers and up to €305,000 on the main component buffers. Additionally, up to €210,000 per year on handling costs can be saved at one specific intermediate buffer.

Another advantage of a Pearl Chain model is that regular components can be delivered Just-In-Time or Just-In-Sequence. The potential savings vary per product group. A sample analysis is performed for some specific product groups. Ultimately, one can conclude that the largest savings on inventory reductions and handling costs are possible for large, cumbersome components which are currently stored in an intermediate warehouse. For future research, TP should analyse what the cost savings can be for other product groups.

1. Introduction

TP is a Dutch truck manufacturing company and a subsidiary of an American company. The American parent company is a global quality leader in the design and manufacturing of high-end light, medium and heavy commercial vehicles. The American company also designs and manufactures advanced diesel engines, provides financial services and information technology, and distributes truck parts related to its main business. The TP headquarters and its main assembly plant are based in the Netherlands. Its core activity is the development, production, marketing, sales and service of trucks for other organisations (Business2Business). Each truck is customised, based on the 'build to order' principle. The engines and sheet metal components are also produced in the Netherlands. The cabs and axles are produced in their plants in Belgium. Some truck models sold under the TP brand are designed and manufactured by their assembly plant in England. At the moment, TP produces three series of trucks. The first series are specialized for city traffic, the second series are for regional, national or international transport and the third series are specialized in longer distances.

The project is conducted at the Quality & Continuous Improvement department in collaboration with the IT department. TP wants to move towards a Pearl Chain model. In this concept, the production sequence of orders is determined beforehand and should be set in stone. As a consequence, materials can be delivered by suppliers via the Just-In-Sequence (JIS) method. A Pearl Chain improves the planning reliability for suppliers as well as the possibilities for optimization of (safety) stock. Therefore, Pearl Chain is typically paired with JIS supply. However, due to the high customization (i.e. a complex Bill-Of-Materials) and a complex supply chain network, the road towards the Pearl Chain model is challenging for a truck manufacturer like TP. More specifically, the current Assembly Production Control model at TP is currently set up too high-level (i.e. on a daily level) and it is not transparent enough to be able to implement a Pearl Chain model. Therefore this research needs to be conducted, before any further implementations can be made.

The reason why TP wants to move towards a Pearl Chain in combination with JIS supply is because other automotive companies have already walked that road successfully. The benefits of the Pearl Chain model are described in the scientific literature. Since 1997 the production of the Mercedes-Benz A-Class in Rastatt is planned according to the Pearl Chain Concept (Weyer, 2002). The Porsche plant in Zuffenhausen also defines a target sequence at the beginning of the construction of a carcass. According to their own declaration this target sequence is maintained for 99% (Kahmeyer, 2002). This shows how good Porsche is in controlling their material flow. Porsche also has built a fully automatic paint shop which is based entirely on the Pearl Chain concept (Scheffels, 2012). The story of Volkswagen has its origin in a collaboration between the University of Applied Sciences and Volkswagen Sachsen in Zwickau, Germany. This plant became a pilot for implementing the Pearl Chain Manufacturing Organization in 2007. It was one of their first attempts to introduce the new integrated Volkswagen production system (Casper, 2007). Now, the Pearl Chain concept is an element of the "new logistics concept". The Audi production in Neckarsulm serves as a reference plant for implementation of the Pearl Chain Concept across the Volkswagen-Group (Seeman, 2015).

The application of the Pearl Chain method in the automotive industry shows that a stable order sequence can optimise production. An early order planning targets a high capacity utilisation and ensures a continuous production flow. A 'calmed' production process responds positively to everyone involved in the process of value creation (Copaciu, 2013). The given examples are all of manufacturers of passenger cars, because no examples could be found for truck manufacturers in the scientific literature. For truck production, they use a body on a frame. These frames are heavier, more rigid and durable than the frames of cars and they allow them to transport heavier loads without deforming. These frames are used for pickups and large SUVs. Cars commonly use a unibody design. In this case, the body of the car itself is the frame. This is the difference between truck production and car production and it can therefore be stated as a research gap for this project. After all, the production between trucks and cars does not differ very much which makes it interesting to investigate this topic. Car and truck manufacturers both use the same assembly process where all parts are produced separately and assembled at the end.

The problem for TP is the fact that it is not easy to move towards a Pearl Chain. Enough examples can be found of other automotive producers who implemented Pearl Chain successfully. However, every case is different. TP needs a customised plan on how to proceed. At TP they already use sequencing and a lot of the materials are already delivered according to the Just-In-Sequence method. However, the lead times of the current production model are not flexible enough and the time units are too roughly estimated (i.e. days instead of minutes). Before further implementations can be made the current Assembly Production Control model should be analysed and evaluated. The current challenges which prevent TP to move to the Pearl Chain concept should be mapped. Then, the process needs to be redesigned so that in the future the Pearl Chain can be implemented as efficiently as possible. Additionally, TP wants to move from their original ERP system to SAP. Therefore the new Pearl Chain model should fit the SAP program. The main goal of this project is to design a Pearl Chain model for a truck producer like TP, based on the latest insights in literature and best practices. TP will use this model as input for a possible future system implementation.

The main goal of this research is to design a Pearl Chain model for a truck manufacturer like TP. In that way suppliers can deliver the materials via the Just-In-Sequence method. The model will be used as input for a possible future system implementation. Therefore the main research question reads:

"How to design a Pearl Chain model with JIS supply for a truck manufacturer like TP?"

To find this optimal Pearl Chain model, a couple of steps need to be taken. These will be further defined by the following sub-questions:

1. ***What are the opportunities and challenges specific to automotive companies when implementing Pearl Chain with JIS supply?***
2. ***How to adapt current Pearl Chain models with JIS supply for the truck industry?***
3. ***How to evaluate a Peal Chain model with JIS supply?***
4. ***What are the possible opportunities and future challenges when implementing the Pearl Chain model with JIS supply in the truck industry?***
5. ***How and to what extent will the new model be supported by SAP?***

The sub-questions and the research methods are elaborated in chapter 2. Then the scientific background of Pearl Chain and JIS is given in chapter 3. Chapter 4 describes the supportive processes which are needed to build a truck assembly, while chapter 5 describes the assembly process itself. In chapter 6, new information is given about the Pearl Chain concept and insights from this information are applied on the current TP processes. Chapter 7 describes the development and the results of the current state simulation, while chapter 8 describes the development and the results of the future state simulation. In chapter 9, cost savings are calculated when certain components can be delivered in sequence. Chapter 10 presents the conclusion of this research.

2. Research Methods

In this chapter, the research methods of the project are elaborated per phase. The Design Science methodology of Wieringa (2014) is used to divide the project into four phases. The Design Cycle framework is given in Figure 1. The project starts with the problem investigation. After that, the treatment design and the treatment validation phases follow. The project ends in the treatment implementation phase. The cycle is done once, so the implementation evaluation is no part of this research. The Design Science Methodology is used to design a Pearl Chain model in combination with JIS supply for TP. In this case, the new Pearl Chain model can be called the artifact that will treat the stated problem. The initial research proposal can be found in the Appendix.

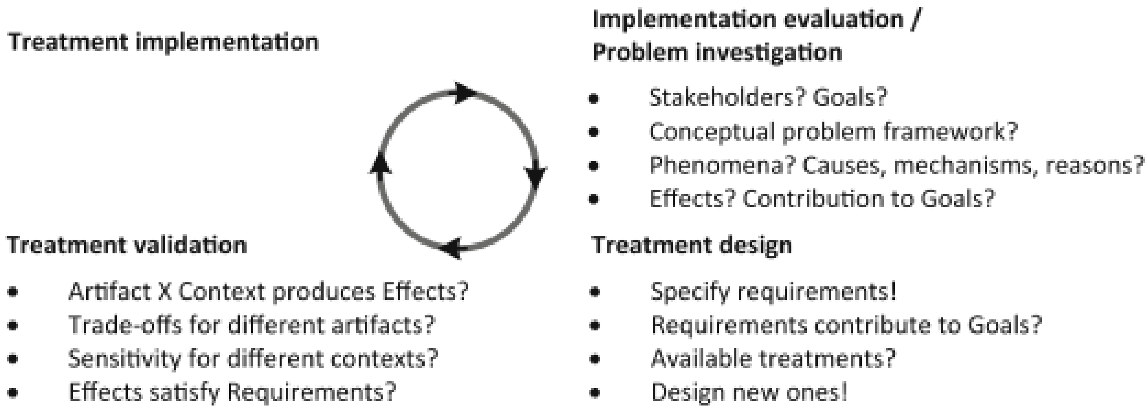


Figure 1: Design Cycle (Wieringa, 2014)

2.1. Problem Investigation

> 1. *What are the opportunities and challenges specific to automotive companies when implementing Pearl Chain with JIS supply?*

For this project, literature about the concepts 'Pearl Chain' and 'Just-In-Sequence' needs to be gathered and assessed. The artifact used is the methodology presented by Randolph (2009). He describes the stages of conducting a literature review. The taxonomy of the literature review can be classified according to six characteristics: focus, goal, perspective, coverage, organisation and audience (Cooper, 1988). The taxonomy of the literature review is given in Table 1.

Table 1: Taxonomy of the literature review

WHAT	HOW
FOCUS	Research methods/outcomes and applications with regard to Pearl Chain and/or Just-In-Sequence method
GOAL	Integrate all the gathered information
PERSPECTIVE	Neutral point of view
COVERAGE	All open source scientific articles in English, Dutch or German
ORGANISATION	Conceptual format based on Pearl Chain and Just-In-Sequence method
AUDIENCE	Practitioners in the field and scholars who are specialised on the given subjects

A short summary of the literature review is given in chapter 3. Randolph describes the stages of conducting a literature review. These stages are followed during the literature review. They are formulated as follows:

1. Problem formulation
2. Data collection
3. Data evaluation
4. Analysis and interpretation
5. Public presentation

> 2. *How to adapt current Pearl Chain models with JIS supply for the truck industry?*

Information should be gathered about the Assembly Production Control model and the assembly process. To gather information about a process, one should follow that process from start to finish. That means interviewing the stakeholders and documenting every step of the specific process. An unstructured interview format is used to get a better understanding of the production control processes at TP. First, the current state processes are visualised. Thereafter, the current state is evaluated based on relevant KPIs with the help of a simulation model. The used methods for the visualisation and the simulation are specified in sections 2.2 and 2.3. The analyses that are conducted during the problem investigation phase are summarised in Table 2. After all the needed information is gathered, the second sub question can be partially answered.

Table 2: Performed analyses of the problem investigation phase

ANALYSIS	GOAL	CHAPTER
LITERATURE REVIEW	Gain basic understanding about the Pearl Chain concept	3
ASSEMBLY PRODUCTION CONTROL MODEL	Interview stakeholders of the supportive processes that are needed for a truck assembly and visualise the processes in a process diagram.	4
ASSEMBLY PROCESS	Interview stakeholders of the primary processes that are needed for a truck assembly and visualise the processes in a flow chart.	5
ASSEMBLY PLANT SIMULATION CURRENT STATE	Investigate the performance of the current order sequence.	7

2.2. Treatment Design

The literature review should give some basic understanding about the Pearl Chain concept. Additionally, Pearl Chain experts are interviewed to gain more knowledge about the implementation of a Pearl Chain model. Requirements for implementing a Pearl Chain model with JIS supply are learned from practical examples. These insights are used to design a future state Pearl Chain model for TP. To answer Q2 a couple of artifacts are used. For designing the process models, the Business Process Model and Notation is used. Business Process Model and Notation (BPMN) is a standard notation used to capture business processes, especially at the domain analysis and advanced system design levels. More on BPMN can be found in "Semantics and analysis of business process models in BPMN" (Dijkman et al., 2008). The tool used for drawing the process charts is Bizagi Modeler. Bizagi provides an open source business process management (BPM) suite whose key functions include the modelling, automation and execution of business processes. The softwares process modelling tools enable managers to use drag and drop capabilities to build visual business processes. That is why Bizagi is used for these activities. Table 3 summarises the analysis that is performed in the treatment design phase. It is possible to answer the second sub question after these analyses.

Table 3: Performed analysis in the treatment design phase

ANALYSIS	GOAL	CHAPTER
TOWARDS A PEARL CHAIN	Interview Pearl Chain experts about the possible implementation of a Pearl Chain model. Identify the potential challenges and visualise a future state process model.	6

2.3. Treatment Validation

3. *How to evaluate a Peal Chain model with JIS supply?*

A simulation is developed of the future state to detect the potential opportunities of a Pearl Chain model with JIS supply. The same method is used in the first phase to investigate the current state (Q2). From the analyses in the previous phases, a couple of KPIs are determined. The average buffer occupation, the average lead time and the amount of blockings before the assembly are important KPIs to analyse. These KPIs are analysed with the help of the simulation model. When the simulations for both the current and the future state are finished, it is possible to compare the current state with the future state in a simulation study based on the important KPIs. The simulation study will fill a research gap in the scientific literature, since Pearl Chain model applications are not evaluated very well in a quantitative manner. The simulations are developed in TP's simulation tool which is called Plant Simulation. Plant Simulation is a software tool developed by Siemens. The tool enables the development of a visualised simulation model with standard features. It provides an additional possibility of algorithmic programming to regulate certain behaviour in the model. The simulation is used to analyse the inventories of WIP trucks and the main components. To analyse the potential inventory reduction on regular components, some sample calculations are performed. Chapter 9 describes the potential cost savings for drive shafts, headlights and 3D laser components. Table 4 summarises the analyses performed in the treatment validation phase.

Table 4: Performed analyses in the treatment validation phase

ANALYSIS	GOAL	CHAPTER
ASSEMBLY PLANT SIMULATION FUTURE STATE	Investigate the potential benefits of a Pearl Chain sequence regarding the WIP and the main components	8
SAVINGS ON SEQUENCING	Investigate the potential benefits of a Pearl Chain model regarding the regular components	9

2.4. Treatment Implementation

4. *What are the possible opportunities and future challenges when implementing the Pearl Chain model with JIS supply in the truck industry?*
5. *How and to what extent will the new model be supported by SAP?*

The final phase is used to present the results, determine the conclusions and give recommendations. No implementation will take place, only advice is given for possible future implementations. The interviews with the domain experts in the problem investigation and the treatment design phase should give a lot of insights which are important to keep in mind during a future implementation. Next to this, the validation phase should identify potential benefits. In the implementation phase the opportunities and challenges are analysed. Solutions for the challenges are brought forward. The potential opportunities of implementing a Pearl Chain model with JIS supply at TP are summarized. In other words, will the implementation of a Pearl Chain model at TP lead to for example a lower lead time and lower costs. Additionally, a check is performed to find to what extent the new model will be supported by SAP, since TP wants to transfer their business to this ERP system. Lastly, the final conclusions and recommendations are drafted and the project is finalized.

2.5. Deliverables

In Table 5 the deliverables per phase are presented:

Table 5: Deliverables per phase

DESIGN PHASE	DELIVERABLES
PROBLEM INVESTIGATION	• Literature review about the concepts 'Pearl Chain' and 'JIS' • Summary of the interviews with stakeholders of the current process • Visualisation of the current Assembly Production Control model • Visualisation of the assembly process • Simulation of the current order sequence
TREATMENT DESIGN	• Summary of the interviews with the Pearl Chain experts • Visualisation of the future Assembly Production Control model
TREATMENT VALIDATION	• Simulation of potential future order sequences • Simulation study of the current state vs the future state • Cost analysis for regular components
TREATMENT IMPLEMENTATION	• Final conclusions and recommendations

3. Scientific Background

Chapter 3 is used to elaborate on the scientific background of the research. The concepts Pearl Chain and Just-In-Sequence are shortly discussed followed by some applications of these concepts in the automotive industry. The full literature review can be found in the Appendix.

3.1. Pearl Chain

A couple of insights are derived about the Pearl Chain concept. The Pearl Chain model is a method that is widely used in the automotive industry. The origin of the Pearl Chain lies in Germany where it was introduced in one of the Mercedes plants in the 1990s. The Pearl Chain is defined by a stable order sequence which is maintained by implementing a frozen zone. In the frozen zone no changes to the order sequence are allowed. By maintaining a stable order sequence, parts can be delivered via the Just-In-Sequence method. The advantage of this method is that inventories can be decreased which saves costs. Unger & Teich (2009) propose a framework on how to implement the Pearl Chain method for synchronous production. The presented framework can be used as a guideline for the implementation of Pearl Chain at TP. Unger & Teich outline the procedural model for implementing this Pearl Chain concept in general implementation guidelines. For the target operating structure, the lean-oriented Pearl Chain basically requires process redesign, process measurement and process control concepts to support agile but stable processes.

The European automotive industry is characterized by complex and customized products. This requires the most complex production planning to arrange various variants in a way that balances the deployment of workers and avoids production peaks. That is why planning assistance methods are presented. Mayrhofer et al. (2011) discuss planning assistance of Pearl Chain forecasting and personnel assignment planning of sequential assembly lines. Procedures are given which can help level the production and prevent overloads with the aim of using a high capacity utilization. Furthermore, a couple of measures are presented in the scientific literature. These measures can be used as KPIs to assess the performance of the Pearl Chain model in simulations and in real life. Next to this, Meissner (2010) presents hedging methods which can help improve the process control. Lastly, to avoid tunnel vision, an application of Pearl Chain outside of the automotive industry is discussed. Tomanek (2018) presents the application of Pearl Chain in hospitals. The adaptation of the Pearl Chain concept is based on the idea of a stable sequence of patients in the operating room on the day of surgery. It aims to improve patient satisfaction through reliable plans. Based on the results, it is not possible to transfer the Pearl Chain concept to hospitals as a whole. However, it can improve efficiency when applied correctly. It is possible to conclude that the Pearl Chain concept works better in a production environment.

3.2. Just-In-Sequence

The origin of the Just-In-Sequence method lies in the 1980s and 1990s at Daimler and Toyota where they started sourcing seats from external suppliers following this method. An integration of the supply chain is needed when implementing the JIS method. It requires a close collaboration between suppliers and buyers. Furthermore, a good IT structure is essential. When implemented correctly, a lot of inventory costs can be prevented. Nowadays, different frameworks exist on how to procure components according to the JIS method. Bányai & Bányai (2017) introduce how to model JIS supply of a manufacturing process. The logistics process integrates the supply chain of the production companies. Nowadays, Just-In-Time based material supply methods are becoming more and more important because they are flexible, reliable and they significantly increase cost efficiency. Build-to-Sequence, Pick-to-Sequence and Ship-to-Sequence are distinguished. A careful consideration should be made on which JIS method to use.

A way to handle the logistic processes for a Pearl Chain in the automotive sector, is to use milk runs (Conze et al., 2013). A milk run is a delivery method used to transport mixed loads from different suppliers to one customer. Milk runs in combination with a Pearl Chain and JIS supply can ensure fully loaded trucks. Compared with other transport modes, milk runs require more planning and coordination. However, case studies show that the potential can be increased under the right conditions. For the German freight area up to 60% of transportation costs can be saved. Additionally, inventory costs will also lower, since the JIS concept is used.

Several models are found in the literature, which define the conditions that support the following decision: when is the need to change Just-In-Time (JIT) supply to JIS (Wagner & Silveira-Camargos, 2011)? A few proposition are made. A minimal variety level of a module is needed if JIS sourcing is to be considered. Next to this, JIS sourcing is more advantageous for modules with a higher value. Furthermore, when the logistic complexity of a module is increased, the space requirement and the handling costs significantly decreases since a complex logistic process like JIS can help to ensure lower inventories. In the automotive industry, interest in JIS supply is increasing day by day.

JIS has been introduced to decrease inventories. Buffers are often identified as waste (muda). It is very inefficient to remove uncertainties in the production process by holding sufficient inventory for all the different parts and assemblies. Despite its benefits, a synchronisation is needed of production systems in a supply network. Numerous risks are determined which should be optimized. Different risk sources in automotive supply networks with JIS are described by Wagner & Silveira-Camargos (2012). Methods to manage these risks are elaborated. In other literature new JIS technologies are presented which should boost the supply chain effectiveness of the automotive industry (Papoutsidakis et al., 2021).

3.3. Current Applications in Automotive Sector

A lot can be learned from practical examples. The supply cockpit which Nedcar had written (Brenner et al., 2003), gives great insights on how to implement a Pearl Chain model with JIS supply. The planned Pearl Chain includes 7-day orders, with approximately 1,200 orders per day. The next day is planned in the early afternoon and then added to the end of the existing Pearl Chain. The Pearl Chain is also the basis for the planned inbound supply, and the supply must cover the demand generated by each pearl in the chain. One learns how the process should be adapted to fit the new model. By researching inventory accounting, coverage calculation, full truck load calculation, alert generating & monitoring and system trailer yard call-offs, great steps can be made towards a Pearl Chain model. These main system functions are also important for TP, since their business is very similar to Nedcar. Using practical examples of related businesses can be very beneficial.

What can be learned from Porsche's paint shop in Zuffenhausen (Scheffels, 2012), is that innovative thinking improves the performance of the Pearl Chain. Porsche uses state of the art techniques which give them the capability to use meticulous planning. Their process is for a large part based on the use of shuttles and robots. These shuttles and robots ensure that nothing can go wrong during the process. In this way, it becomes possible to deliver perfect quality at every time. The process has been made flawless. The risks are minimized which ensures that the Pearl Chain sequence can be perfectly maintained. So if TP wants to implement the Pearl Chain, they should also consider to lift their production process to the next level by implementing new and more advanced techniques.

The use of SAP at suppliers of Automotive parts shows that this ERP system can be very beneficial for the whole supply chain (Lorenc & Szkoda, 2015). SAP has great system functions, which flourish even more when the supply chain is integrated with the help of SAP. A whole procedure is given which could help TP and its suppliers during the implementation of Pearl Chain. Summarizing, if TP can map their system requirements, develop advanced production techniques and integrate its supply chain, the Pearl Chain future will be closer than ever.

By elaborating on the previously mentioned literature and contributing to TP's specific wishes a balance is maintained between the rigor of this research and its scientific relevance. A lot of scientific literature is found about the terms 'Pearl Chain' and 'Just-In-Sequence' and this literature will be used to improve the scientific relevance of the research. Next to this, the wishes of TP are carefully considered to ensure that the project also is rigorous. The truck industry and quantitative analyses in a production environment are not represented in the literature and these subjects are therefore stated as the research gap for the current research.

4. Assembly Production Control Model

In this chapter the Assembly Production Control model is elaborated at the hand of a BPMN (Business Process Model and Notation) process diagram. The Assembly Production Control model explains all the supportive processes which are needed for the assembly of a truck. The diagram explains which parties are involved in the process and what their contribution is to the realisation of a truck assembly. The organizational units involved are the Marketing & Sales department, Production Control, Logistics, the Production Plants and the Suppliers. In principle, every truck needs to walk through this process. However, for efficiency purposes, batches of multiple trucks are moved through the process. The batch size depends on the process step. Figure 2 gives the first part of the process. Figure 4 gives the second part of the process. The process steps are elaborated in this chapter. The corresponding activity names are displayed in bold and cursive in the text. The full process model can be found in the Appendix.

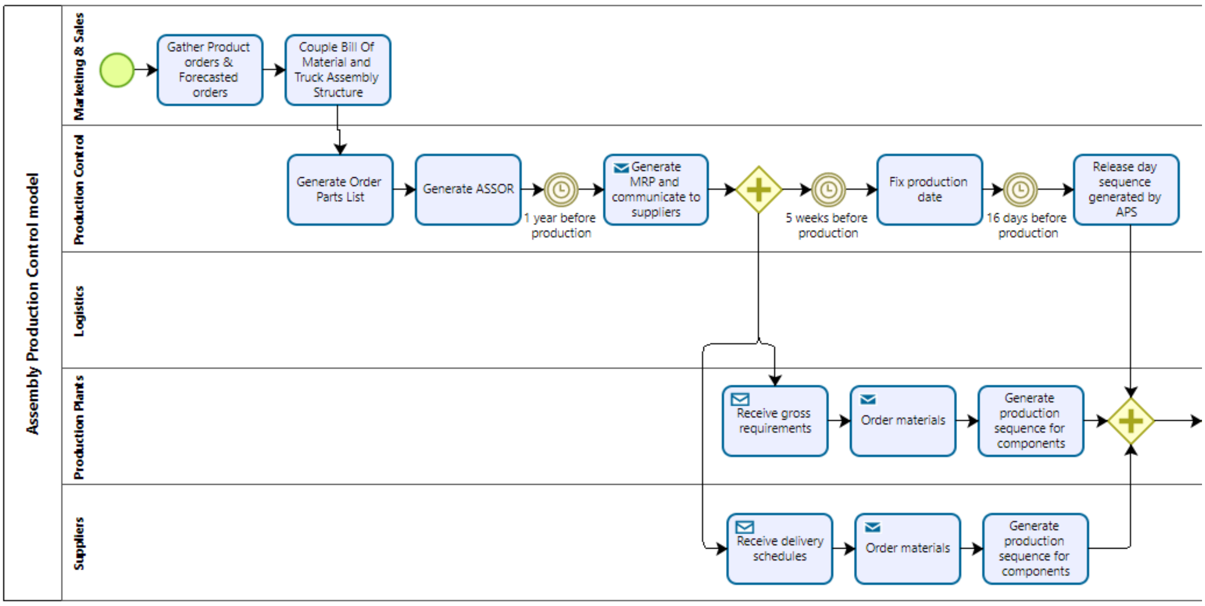


Figure 2: Assembly Production Control model – Part 1

4.1. Marketing & Sales

The process starts at the Marketing & Sales department where trucks are directly ordered by customers ***(Gather Product orders & Forecasted orders)***. Next to these direct orders, the Marketing & Sales department also estimates how much trucks TP can sell in a certain time period. Therefore, forecasted orders are generated. The forecasted orders are not customer specific. These orders still have to be customized. Forecasted orders are used in order to fill the capacity and to know the amount of needed materials for when production is nearby. Orders are automatically coupled to a Bill Of Material (BOM) and a Truck Assembly Structure (TAS) ***(Couple Bill of Material and Truck Assembly Structure)***. The BOM indicates what materials are needed for the production. The TAS states in what way the materials are assembled together to ultimately form the new truck.

4.2. Production Control

When the BOM and the TAS are available for a specific truck, the Order Parts List (OPL) is generated ***(Generate Order Parts List)***. The OPL system contains all the information about the needed materials, how these materials need to be assembled and which work places and machines are needed for the process. It includes specifications from both the BOM and the TAS. However, where the TAS includes mainly high level instructions, the OPL also contains work instructions on a lower level which are important for the line operators in the production and assembly plants. During the production, the work instructions are communicated to the operators with the help of the MES system. This system displays the work instructions on screens in the plants. When the OPL is generated, an Assembly schedule is produced ***(Generate ASSOR)***. This schedule is called the ASSOR (which stands for Assembly Order) and it simply visualises when and where (in which plant and which station) the components are produced and the truck is assembled. Additionally, it indicates when and where materials are needed. These moments are represented by MBS (Materiaal BeSchikbaarheid = Material Availability in English). The ASSOR is displayed in Figure 3. The named applications are all part of the TP Mainframe. The functional design of these applications is maintained by the Production Control department. Ultimately, the applications are developed by the IT department. Production Control is consulted during this process.

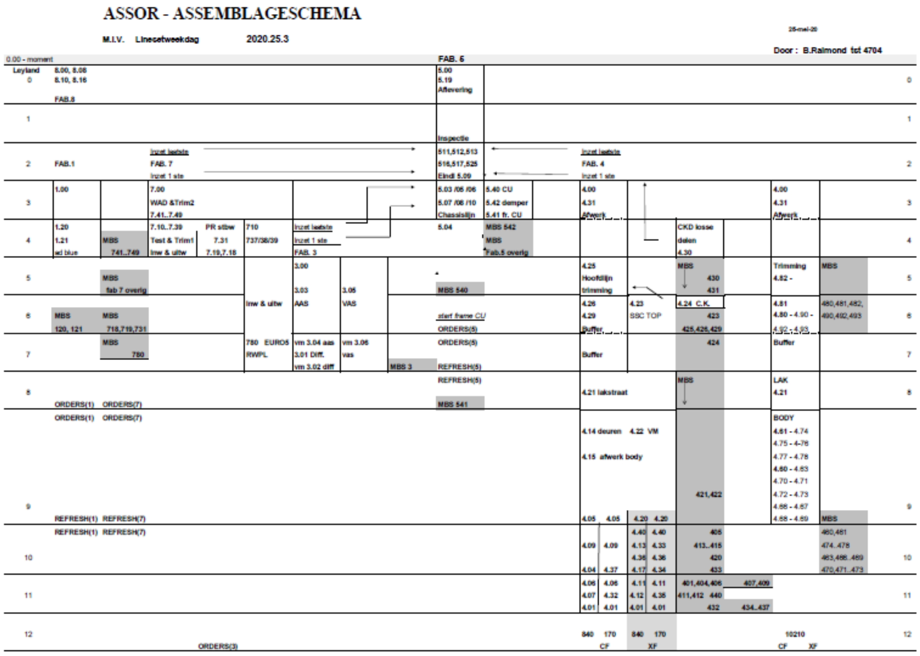


Figure 3: ASSOR schedule (Raimond, 2016)

One year before the production, the Material Resources Planning is communicated to the suppliers and the production plants of TP in the form of delivery schedules for suppliers and gross requirements for internal plants ***(Generate MRP and communicate to suppliers)***. The production date is fixed five weeks in advance ***(Fix production date)***. 16 days before the production date the day sequence is released ***(Release day sequence generated by APS)***. The sequence is generated with the help of an APS (Advanced Planning and Scheduling) system. At the end, Production Control is responsible for the management and control of the assembly process. This department creates the assembly sequence and it makes sure that this sequence is maintained as much as possible. The assembly sequence created by Production Control is used to create the sequences in the other production plants. Production Control is also responsible if trucks have to be blocked ***(Block truck & move other trucks forward in sequence)***. This happens when components are not delivered on time or if the delivered components are of bad quality. Three to four hours before the assembly the truck is frozen on the sequence ***(Freeze truck on sequence)***. Then, the assembly can start which is directed by Production Control ***(Assembly)***. More information about the assembly process is presented in chapter 5.

4.3. Logistics

The Logistics department is responsible for the movement of components between the plants and the warehouses ***(Transport to VRS location)***. Next to this, Logistics is also responsible for the movement of components in the plants. Components are moved from an one of the warehouses to different VRS locations (Voortgang Registratie Systeem = Progress Registration System in English) in the assembly plant. Each plant has multiple VRS locations. At these locations, the position of the trucks and the main components are automatically registered in the TP Mainframe. In this way, it is possible for TP to monitor the progress of every product. One can find the exact location of every product with the help of the VRS system. At the TP site in the Netherlands, there is a Central Parts Warehouse where different parts are delivered for intermediate storage ***(Store in warehouse and pick/sequence components)***. The three different plants in the Netherlands also have a smaller warehouse (supermarket) in the plant itself. Parts from the Central Parts Warehouse are delivered Just-In-Time or Just-In-Sequence to these plants. Additionally, parts are directly delivered from the supplier to the plant according to the JIT or JIS method. Product specific parts which are expensive to store are delivered Just-In-Sequence or Just-In-Time. JIT parts are delivered in batches to the assembly plant. JIS parts are directly delivered to the assembly plant in the correct sequence. Parts which are less expensive to stock are stored in one of the warehouses. Parts are picked with the help of the Kanban system (for general materials) or sequenced with the help of the SA/SK method (for product specific components). The SA/SK method is elaborated in section 5.3 Finally, the components are delivered to a specific VRS location.

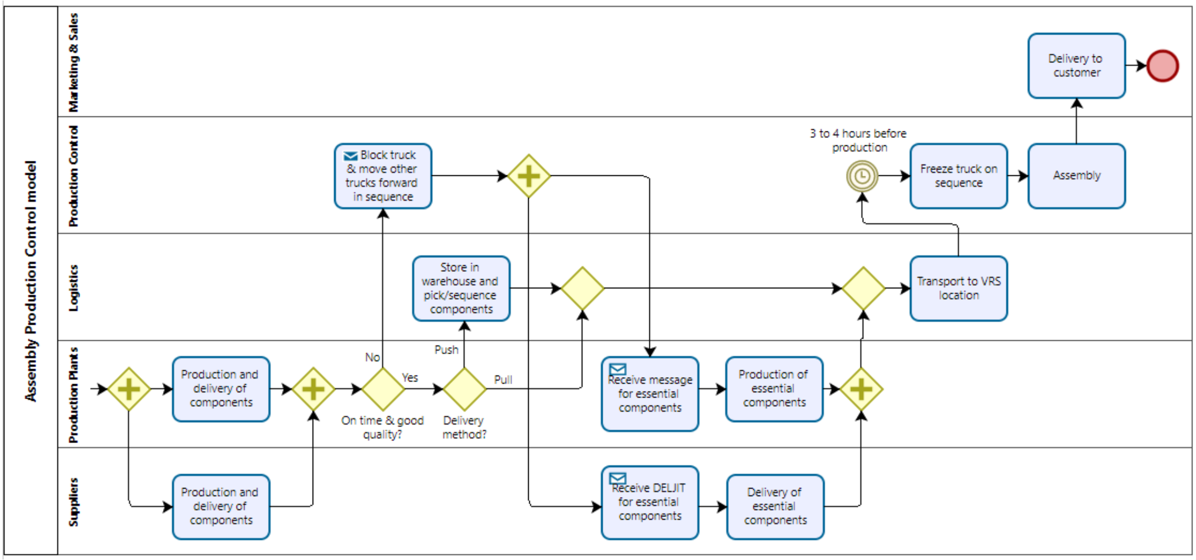


Figure 4: Assembly Production Control model – Part 2

4.4. Production Plants

TP has several production and assembly plants. Three plants are based in the Netherlands, two plants in Belgium and one assembly plant in the United Kingdom. One assembly plant is based in the Netherlands. What happens in this plant is managed and controlled by the Production Control department. Next to this, there is an engine plant and a sheet metal components plant based in the Netherlands. The cabin plant and the axle plant are based in Belgium. The TP assembly plants in the Netherlands and the United Kingdom are the main customers of the TP components plants ***(Receive gross requirements)***. However, these plants can also deliver to other customers. The production plants where components are manufactured can be seen as direct suppliers of the assembly plants. The plants order their materials independently ***(Order materials)*** and they generate their own production sequence ***(Generate production sequence for components)***. This production sequence is largely based on the sequence that is released by Production Control. When the original assembly sequence changes, the production plants are notified ***(Receive message for essential components)***. In order to maintain this new assembly sequence, essential components are moved forward in their production sequence ***(Production of essential components)***.

4.5. Suppliers

TP has multiple suppliers for a various assortment of components. The role in the Assembly Production Control process for suppliers is very similar to the role of the production plants. First, they receive purchasing orders for the components. ***(Receive delivery schedules)***. Their job is to deliver the push components to one of the warehouses or the pull components directly to the assembly plant ***(Production and delivery of components)***. A truck is blocked when a change in the original sequence is implemented by Production Control. Essential components are needed earlier in the process because of that change. When these components are not on stock, a DELJIT message is sent to the suppliers ***(Receive DELJIT for essential components)*** in order to receive these components on time. Suppliers are, in contrast to the production plants, external parties. Therefore direct communication is slightly more difficult. By using DELJIT messages, the communication between TP and its suppliers is smoothened.

4.6. Challenges

The current Assembly Production Control model knows several challenges which prevent TP from implementing the Pearl Chain method in its purest form. At TP, they work according to the block-to-build principle. This differs from the Pearl Chain method, since trucks which cannot be built because the relevant components are not ready, are blocked and produced another time. On the other hand, the Pearl Chain method strives to maintain the original sequence which is predetermined for at least a week. Therefore, the problem is that TP currently cannot maintain its original sequence. There are different factors which make it hard for TP to maintain the original sequence.

Firstly, the plants in the Netherlands and Belgium have calendar differences. That means that these plants have different holidays. When the cabin and axle plants in Belgium have some days off, a lot of buffers are produced in Belgium to cover these holidays. This does not necessarily influence the order sequence in the Netherlands. However, difficulties occur regarding the management of materials for the plants in Belgium. The Netherlands calendar is used to configure the delivery schedules of JIS components from suppliers to the cabin and axle plant. The problem corresponds to the activity ***'Production and delivery of components'***.

Another factor is that the Customer Order Decoupling Point (CODP) at TP lies very early in the process. A TP truck is customer specific from the moment that the order is placed by the customer at the activity ***'Gather product orders and forecast orders'***. Every truck that TP produces is different. The produced main components are already customer specific so it is not possible for TP to create inventories of anonymous parts for sequence components. This makes it harder for TP to maintain a Pearl Chain, since every component should be made in the correct order. It is not possible to produce main components in advance to guarantee a feasible Pearl Chain.

Rework is also a considerable problem in the production plants. When parts are not of the required quality, they need to be manufactured again or repaired. This leads to a delay in the assembly schedule since components are not ready on time. In the worst case it means that the truck cannot be produced at the time of the original sequence. This means that the specific truck needs to be blocked and produced another time. Rework is caused in the activity ***'Production and delivery of components'.***

The Pearl Chain method suggests a frozen zone of at least one week. At TP they do not reach this standard. The assembly plant in the Netherlands maintains a frozen zone of about three to four hours. The frozen zone is defined by Production Control in the activity ***'Freeze truck on sequence'***. The other production plants of TP maintain approximately the same frozen zone length. A short frozen zone means that Just-In-Sequence delivery of components with a long lead time can be problematic. In this case, only components from nearby suppliers can be delivered in sequence directly to the assembly line. Components with long lead times should be on stock earlier to ensure the possibility of maintaining the original sequence.

The support systems are also discussed. According to different employees from the IT and Production Control department, these systems are not limiting TP to implement the Pearl Chain method. However, improvements to these systems can be made. The possibility exists to integrate the ASSOR and the OPL into one system ***(Generate OPL/ASSOR)***. Unfortunately, this could be a very costly project in terms of software and implementation costs. Next to this, the APS system needs an update to maintain a Pearl Chain sequence ***(Release day sequence generated by APS)***. A Pearl Chain needs a bigger frozen zone so the APS system has to calculate more complex sequences than it does now. Currently, the APS system needs to determine a frozen zone of maximum four hours. Furthermore, the production planning at TP is done on day level ***(Generate production sequence of components)***. When TP wants to maintain a Pearl Chain, it should plan on hour or even minute level to ensure the correct material requirements can be determined.

5. Assembly Process

The Assembly Production Control model includes the supportive actions to realise the assembly process. This chapter explains the assembly process which is displayed in the end of the Assembly Production Control model, before the delivery to the customer. First, the assembly plant is discussed, followed by the production process and the sequencing method which is used at TP. Section 5.4 elaborates on the TP sequence score method.

5.1. Assembly Plant

In Figure 5, a map is given of the final assembly plant in the Netherlands and its surrounding buildings. It gives a broad image of the structure of the plant. It is also used to explain the flow of the production process in the next paragraph. Adjacent to the truck factory, lies the engine plant, the sheet metal components plant and the head office. The assembly plant includes places to hold audits and to build prototypes. A receiving dock, a small warehouse and a training booth are also present. The production line takes up the most space. More on the production line is presented in the next paragraph.

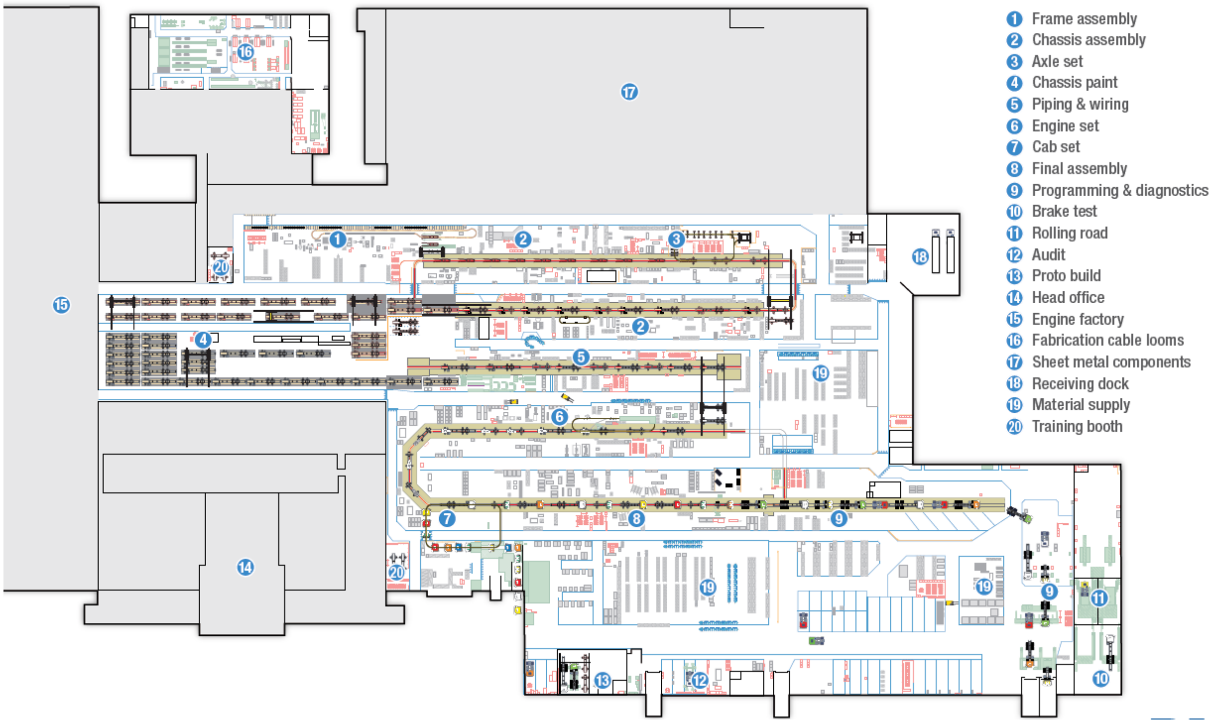


Figure 5: Assembly plant overview (Wiering et al., 2017)

5.2. Production Process

The production process is globally visualised in Figure 6. Since this process does not involve multiple departments, a flowchart is used to visualise the process. The flowchart depicts the flow of the trucks through the assembly line. The numbers of the stations represent the location within the assembly plant. First, the deployment plan (=*Inzetplan* in Dutch) is created. This plan determines the initial order of the truck orders. The deployment plan contains the order sequence for three production days. Every day, the sequence of one production day is added from the line set which already was released 16 days before the production. The order sequence in the deployment plan can still change. The actual start sequence is called the lay down plan. The start sequence is fixed when the truck orders move into the

Hengelhoef. The *Hengelhoef* is a virtual buffer which functions as the frozen zone. It always contains 40 orders. The frozen zone is equal to 40 tact times of approximately 5 minutes. Therefore the frozen zone equals 3 to 4 hours at the TP assembly plant. When a truck is about to be produced, the first step into the production process is the *Skids*. At the *Skids* the frame assembly is created which needs to carry the to be produced truck. After this step, the frame assembly is put on the production line. Then the first part of the chassis is built at *Chassislijn 1*. The axle set is also assembled at this production line. The chassis is finished at *Chassislijn 2*. Then the finished chassis is transported to the paint shop (*Lakstraat*) where it is painted in a standard colour or a customer specific colour. After the paint is applied, the chassis needs to dry for a certain time period. The next step in the process is *Eindlijn 1*. Here the truck gets all the required piping and wiring. At *Eindlijn 2*, the engine and the cab are assembled and the final assembly is performed. Furthermore, the software is programmed and tested. At the end of *Eindlijn 2*, the truck is taken off the production line to *Afband*. Final speed and braking tests are performed here before the truck is moved to the delivery buffer. Between every production line, a buffer is present. The buffers make it possible to adjust the sequence. Truck orders are moved to the buffers when defects occur or certain parts are missing and further production is not possible. Truck orders from the buffers are mixed in the sequence to fill the created gap. Supply buffers for the axles, engines and cabs are also present in the assembly process to ensure a continuous supply of the main components. Five logistic teams ensure the constant supply to the production line. The first team is responsible for *Skids* and *Chassislijn 1*. The second team is responsible for *Chassislijn 2* and *Eindlijn 1*. The third team handles *Eindlijn 2*. Team four is active on the receiving dock. The final team is responsible for the central control of all the logistic processes in the assembly plant.

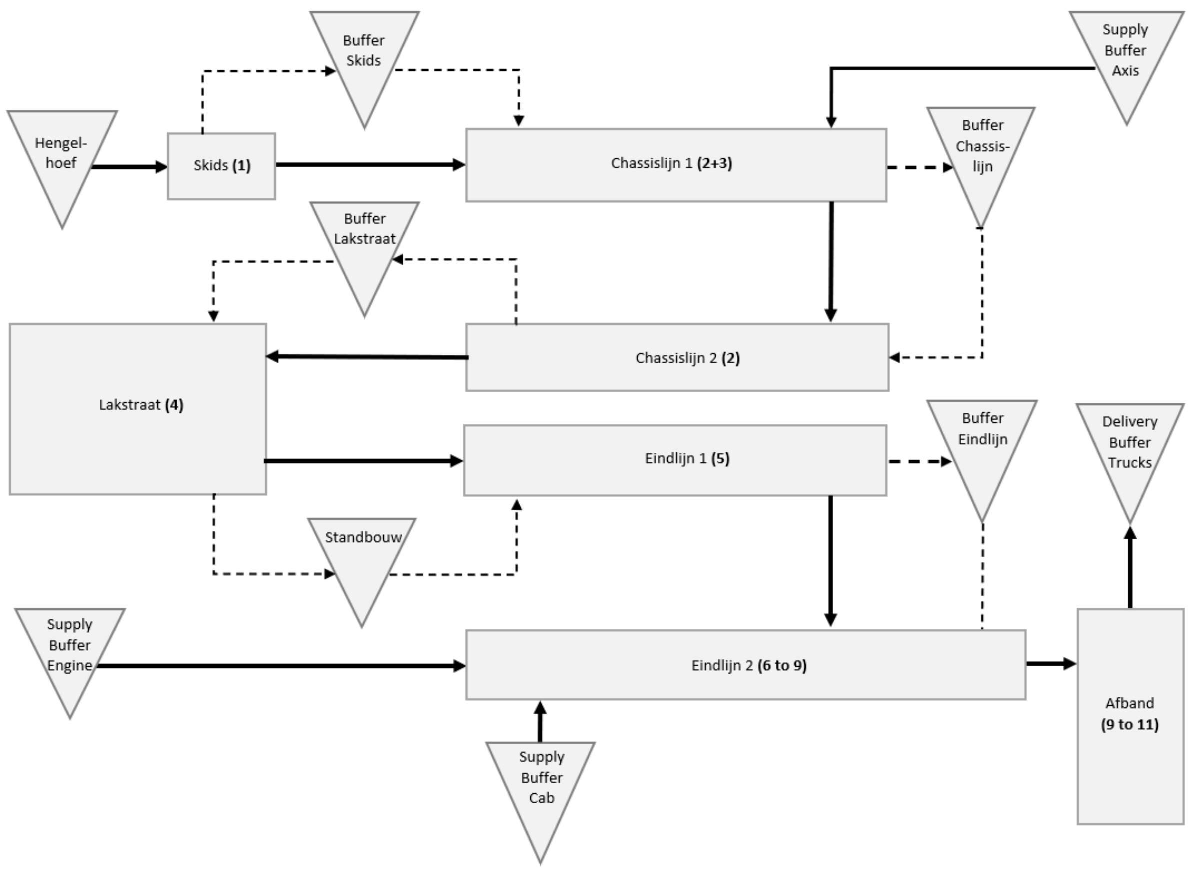


Figure 6: Assembly process overview

5.3. Sequencing of Articles and Kits

Components that are stored in one of the warehouses at TP often need to be sequenced in the right order for the assembly processes. The method which TP uses for sequencing is called Sequencing Articles (SA) when the same components are ordered for multiple orders (Commisso, 2012). It is called Sequencing Kits (SK) when multiple components are ordered in a batch for one specific order. One of the goals of the research is to investigate if the point of sequencing can be shifted to the supplier for more components. That is one of the differences between Just-In-Sequence and regular supply. When TP has to sequence less components, it will decrease their inventories because the central warehouse can be skipped in the process. However, this method is not suitable for all components. It is mainly profitable for large or expensive components because these components have higher storage costs. TP also uses the method Order Kitting (OK) for external suppliers. The OK method is very similar to the SA/SK method. The main difference is that OK is used for external suppliers and SA/SK for internal suppliers. For the future, TP intents to replace the OK method for external suppliers with the SA/SK method because it is easier and more efficient in use.

The main idea of the SA method is that a new component is ordered when the inventory level is not high enough to provide for the critical horizon. The critical horizon is determined by the lead time of that certain component. Suppose that the lead time of a certain component is 75 minutes. So the warehouse needs 75 minutes to get the component to the assembly line at TP. When using the assumption that TP can produce 12 trucks per hour, the takt time is 5 minutes. 75/5=15, so the critical horizon is equal to 15 takt times. The inventory level of the component should therefore be equal to the needs of the 15 trucks which are to be produced. If the component is only needed in 3 of the 15 trucks, the inventory level should be at least 3. When the inventory level is below 3, a new batch of components is ordered which should be at TP within 75 minutes. The SK method includes a secure way of order picking. The pick commands are automatically generated and prioritized. When the wrong article is scanned by the hand terminal, an error message appears. The secure system ensures that the correct combination of components for a specific truck is delivered to the assembly line.

The JIS supply method is more labour intensive for the supplier than the regular delivery method since components are handpicked according to the right sequence at the supplier. Therefore it requires extra delivery costs. When components are delivered to TP according to the regular manner, they are delivered in batches of the same products and stored in a TP warehouse. Other components are delivered in batches of the same product (Just-In-Time) directly to the assembly plant. When needed (in particular for large product specific components), TP employees have to sequence the components in the right order. If the supplier delivers the components according to the JIS method, it has a couple of benefits. The inventory levels within the TP warehouses are lowered and TP can save labour costs since the components are already sequenced by the supplier. The JIS method is particularly suitable for large, expensive articles and slow movers since the savings on the storage costs for these articles outweigh the extra delivery costs. The goal is to use this method on more products to eventually lower the handling costs and the inventory levels in the warehouses. The extra delivery costs of JIS supply should be taken into account in order to decide if sequencing of a product is profitable.

5.4. TP Sequence Score

TP uses a scoring system to measure the sequence stability of the truck orders in the production plants (TP, 2019). This system is used in the rest of the report to indicate the performance of a sequence. The scoring system compares two different order sequences from two different VRS locations. For example, one could choose to compare the order sequence of *Eindlijn 2* with the order sequence on the delivery plan. Generally, this method is chosen to calculate the sequence stability of the assembly plant in the Netherlands. However, it is also possible to compare other VRS locations and calculate a corresponding sequence stability score of these two VRS locations. If the order sequence on the delivery plan is compared with the order sequence of *Hengelhoef*, one finds how many sequence changes happen before the assembly. When comparing *Eindlijn 2* with *Hengelhoef*, one finds the relative sequence change during the assembly. Another possibility is to compare the delivered sequence of the main components with the order sequence on the delivery plan. This will give a good measure on how well the axle, cabin and engine plant align their order sequence to the assembly plant.

The sequence score is calculated by retrieving the deviation per transport number. Five categories are defined which correspond to a certain amount of penalty points. If a transport number does not deviate from the original sequence or the deviation is smaller than 4, 0 penalty points are awarded. If the sequence deviation is between 4 and 12, 1 penalty point is given. A sequence deviation between 13 and 48 means 3 penalty points. Five penalty points are awarded when the deviation lies between 49 and 96. When the deviation is higher than 96, 10 penalty points are given. The different categories are displayed in Table 6.

Table 6: Penalty points per sequence deviation category

DEVIATION	0-3	4-12	13-48	49-96	97+
PENALTY	0	1	3	5	10

The ultimate score is calculated by using the following formula:

Score = 100%*(amount of transport numbers)/(amount of transport numbers + penalty points)

By using this score in the rest of the report, a well-defined measure can be applied to an abstract variable (the order sequence). The sequence score is used to test the sequence stability between multiple VRS locations. The goal is to compare the current sequence score within TP with possible future state scenarios.

6. Towards a Pearl Chain

In the previous chapters, the current state processes at TP are described. The question arises: What does TP need to change when implementing the Pearl Chain method. To answer this question, help is needed. Interviews are held with representatives of the consultancy firms Flexis and Nobleo. These interviews are discussed in section 6.1 and 6.2. Then, an interview with some members from the software firm SAP is discussed in section 6.3. At the end of this chapter, the insights gathered from the interviews are applied on the TP processes. The future state processes at TP are mapped as recommendation for a future Pearl Chain implementation.

6.1. Flexis

Flexis helped the truck producer MAN with implementing the Pearl Chain model. The production process at MAN is very similar to the production process at TP. That means it should certainly be possible for TP to implement a Pearl Chain model. The focus of Flexis lies on the development of a production program and the control of this program (Flexis AG, 2012). The production sequence has a lot variants coupled with constraints. Therefore, it is a complicated job to realise a suitable production program.

6.1.1. Sequencing

Figure 7 shows the development over time of the Pearl Chain sequence at MAN. From 30 days before the production, the orders are placed in buckets. 18 days before the production, the buckets are transferred into a string of pearls. These string of pearls has to meet certain restrictions. For example, it is not allowed to build too many large trucks after each other. Until day 11 it is allowed to swap pearls in the chain. From day 10, the frozen zone is defined. The production sequence is fixed and cannot be changed anymore. The Pearl Chain determines the production sequence, both for complete vehicles and for main components. The sequence stability for complete vehicles and main components is equal to approximately 99%. Only 1% of the orders leads to a sequence disturbance. Nearly all components for which it is profitable can be delivered Just-In-Sequence, Just-In-Time or Supply-In-Line-Sequence because of the long frozen zone. For more information about these three delivery methods, see section Material Flow6.2.3.

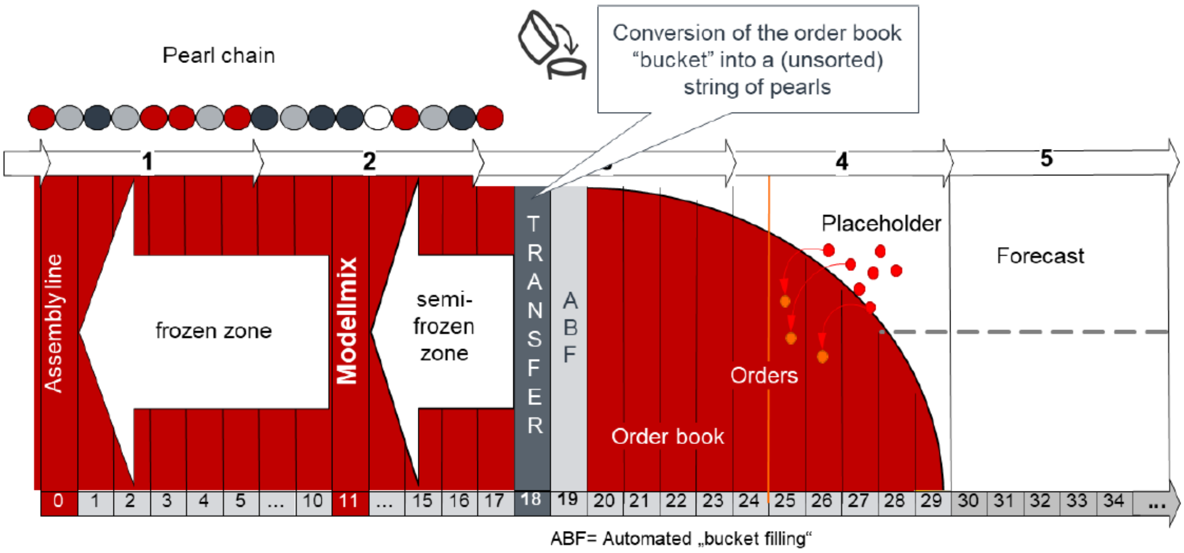


Figure 7: Development of the Pearl Chain sequence at MAN (Flexis AG, 2012)

Flexis designed an APS system which can automatically generate a production sequence which conforms to all the defined hard constraints and most of the defined soft constraints. Hard constraints have to be met while soft constraints are preferably met. The sequencing system helps the user by forecasting the amount of critical attributes in a certain time period. The user can manually override the generated sequence and violations of constraints are visualised. The Flexis sequencing system is already used by both MAN and TP. The system has an easy to use interface and provides a simulation possibility of the sequencing result. First, the orders should be scheduled in the right slot. Then the orders need to be balanced based on their constraints. After that, the orders are set in the right sequence. When needed, new sequence positions have to be found for non-buildable orders. The Flexis system has no limit for the required constraints and rules. It provides stability in planning and execution. The system is transparent and contains visualisations. Next to this, the sequencing tool is also flexible and continuous adaptable.

6.1.2. High Variant Production

In order to keep the variance buildable in an efficient way with constant cycle times, a couple of principles and tools are important:

- Variant oriented design of the assembly line (with flexible working models, e.g. ‘jumpers’)
- Scheduling and Slotting must provide an executable program as much balanced as possible
- The sequencing rules must distribute the vehicles according to the constraints in the assembly line to realise maximum productivity
- The scheduled sequence must be realised as stable as possible (>95% sequence stability)
- Visualisation tools are needed to display the sequence and to be able to react with the personnel deployment that is needed to ensure the constant cycle times. The Flexis system provides a possibility for simulations to find labour intensive spots in the sequence.

These principles are all success factors for a stable high variant production. Flexis can help with solutions for order processing like scheduling and slotting modules, sequencing and resequencing modules and monitoring and visualisation modules. Process support for a successful implementation is also included. Production engineering and the design of the assembly line/structure is not in their abilities. However, Flexis can help connect order processing and production engineering. The Pearl Chain can only be used for logistic purposes if it is kept stable. A couple of factors are important to keep the sequence stable:

- Booking discipline among employees. Preferably, an automated booking system.
- Sequencing is recognized and accepted as a relevant supporter
- Consistent reporting of the sequence stability and the sequence violations
- A malus system for suppliers for late deliveries
- The strategic goal is high sequence stability. Violations should be avoided at all costs!

At MAN, it has taken several years for the Pearl Chain to become stable enough to provide the basis for further process optimizations. It is a process that will gradually increase the sequence stability until the point that the stability is equal to almost 100%. A high sequence stability enables the design of highly sophisticated logistics processes based on the Pearl Chain. It ensures an efficient production and a high delivery reliability/customer satisfaction. MAN succeeded in lowering their early and late orders. Their on time performance (which means that the delivery meets a 4-day time window that was fixed during scheduling) increased from 52% in 2010 to 91% in 2012 (see Figure 8). Consequence is a higher customer satisfaction and lower stocks.

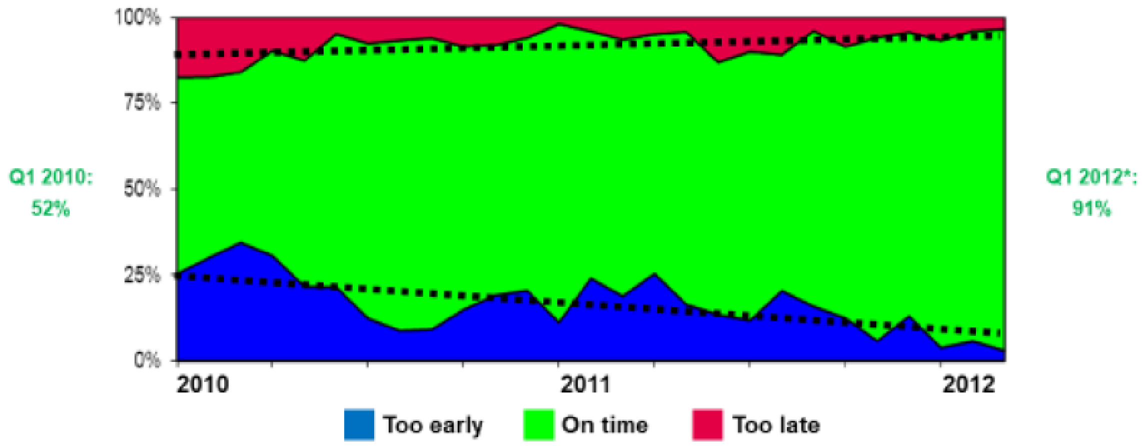


Figure 8: The delivery performance of MAN from 2010 to 2012 (Flexis AG, 2012)

6.2. Nobleo

Nobleo already has experience with implementing the Pearl Chain method at Nedcar and Volvo (Thissen, 2014). Therefore, they can provide a lot of information regarding the subject. The Pearl Chain method is in particular interesting due to the increasing mass customisation for premium European vehicles. This challenge must be shared with the core suppliers.

6.2.1. Lean & Continuous Improvement

The Pearl Chain model is actually a Lean method. The highest focus of Lean is flow efficiency followed by resource efficiency. A couple of differences are distinguished between traditional methods and Lean methods. Lean methods focus on maintaining the sequence and single piece flow. The goal of Pearl Chain is not to keep a stable sequence, but to keep a perfect sequence. When a perfect sequence is maintained, inventories and buffers can be reduced to a minimum. A focus on generating value is essential in the chain. The 9 Pearl Chain principles are:

1. Create Value: Focus on value creating processes
2. Single Piece Flow: Create single piece flow for bodies and main material flows
3. Heijunka: Line balancing to create a constant flow
4. First Time Right: Assume very high levels of First Time Right
5. Zero defect: No defects are required for JIS and JIT deliveries
6. Zero inventory: Think in coverage instead of inventory
7. Andon: Pro-active visualisation of deviations in the flow
8. Pull: Bodies are pulled from previous work stations and materials are pulled from suppliers
9. Manage interdependencies: Building upon excellent performances

Pearl Chain is a strong enabler for three types of improvements. At first, Pearl Chain enables continuous improvement in manufacturing. One should strive for a First Time Right (FTR) when manufacturing products. The delivery precision has to be as high as possible together with an excellent efficiency. Secondly, Pearl Chain also drastically improves the supply chain. Warehouses can be reduced by moving inventories to warehouses on wheels (trailers on parking lots). Supply is based on JIT and JIS flows. Strategic supplier sourcing is the third type of improvement. Move suppliers to best cost countries and share overhead costs for different suppliers.

6.2.2. Sequence Stability

Three major necessities are named for a stable Pearl Chain. First, approximately 10 days before the actual production the Pearl Chain sequence should be released. This sequence needs to adhere to all the sort of mixing rules. Second, to control the sequence a KPI measurement system should be in place. The measurement system needs to indicate when certain mix or sequence deviations occur. Third, when materials are delayed an indication should be received by Production or Logistics. For exceeding delay, a contingency plan needs to be in place. Sequence creation, KPI measurement and delay planning are of major importance for the Pearl Chain concept.

The current activities at TP contain traditional warehousing, intermediate storages, material kitting and pick to sequencing. These are all activities that do not add value. Currently, four percent of all the regular components within TP are pulled. This equals 12% of the yearly turnover in euros for regular components. So for the other 88% of the yearly turnover, inventories are maintained because of an unstable order sequence. By implementing a FTR flow KPI and striving to increase this KPI, a lot of the waste activities can be skipped. In Station Quality Creation (ISQI) can prevent reparations at the end of the process. Controlled in line repair and controlled repair loops are ways to resolve defects at the work station where the defect is discovered. Certain deviations in the sequence are allowed as long as they are pro-actively controlled. A pull system at storages ensures that bodies are pulled in perfect sequence without re-mixing the chain.

In the car industry, three chances are given to ensure a perfect sequence. If the car is FTR, the sequence is maintained. If the car is not FTR, the sequence can still be maintained if the repair time is smaller than the waiting time in the buffer. The last chance to maintain the sequence is by using body recoupling. Similar bodies are swapped to ensure that the sequence can be restored. The last step is hard to implement in the truck industry because the bodies are already customer specific at the begin of the process. The most cars on the other hand, become customer specific after the paintjob. It is one of the reasons why Pearl Chain is harder to implement in the truck industry. Trucks are simply more complex to build. However, it is certainly possible to implement the Pearl Chain method in the truck industry.

6.2.3. Material Flow

The best solution is to in-source components/materials because it mostly is the cheapest option. Otherwise, far-sourcing in low cost countries (i.e. Eastern Europe) is the most profitable. When the frozen zone is long enough, components from Eastern Europe can still be delivered Just-In-Sequence. The pillars of the Pearl Chain method are flow based inbound logistics (also known as JIT) and sequential deliveries (also known as JIS). JIT ensures deliveries in Pearl Chain lots while JIS ensures deliveries in the exact Pearl Chain sequence. See Figure 9 for a visual explanation of the different concepts. Both types of deliveries can be handled with the warehouse on wheels concept. Inbound logistics are to be stored in a trailer yard. The trailers are coupled to a dock which is used for the line feeding. The trailers are loaded according to a precise loading instruction and they are unloaded with the help of the Kanban system. Synchronisation of production and supply is necessary and sequence stability is an important prerequisite.

With the warehouse on wheels concept, warehouses and intermediate stocks in the plant are redundant. No double or triple handling costs are needed, since the components are unloaded with Kanban from the trailer dock to the assembly line. No more working with large inventories. Only single piece flow (JIS) or Pearl Chain lots (JIT). Supply In Line Sequence (SILS) can also be of use. SILS is a delivery method from nearby suppliers which does not require any warehouses (on wheels). TP uses SILS already for in-sourced components from the engine and the sheet metal plant. SILS is very efficient for in-sourcing, however it can become quite expensive when SILS is used for external suppliers. In that case, sequential deliveries from suppliers in best cost countries are mostly more profitable.

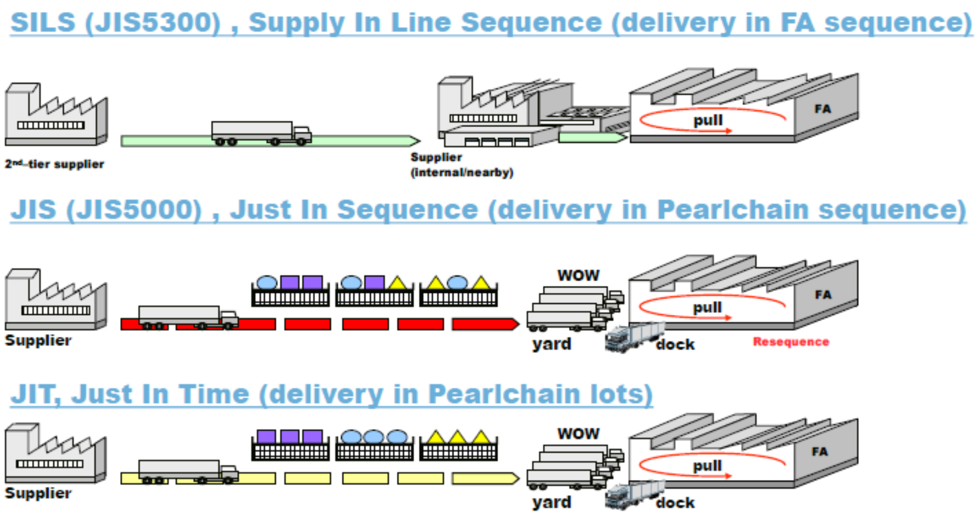


Figure 9: SILS, JIS and JIT visually explained (Thissen, 2014)

6.3. SAP

The intention of TP is to replace their current ERP system: the TP Mainframe. The main candidate to replace the TP Mainframe is SAP. Employees of SAP are consulted during this research. It is important to know if SAP can provide the system requirements for a Pearl Chain model. In the following paragraph the main system functions of SAP regarding a Pearl Chain model and JIT/JIS material flow are described (SAP, 2021). The SAP system includes the Rapid Planning Matrix. The Rapid Planning Matrix handles JIT calls. This system contains two different JIT call types. The summarized JIT call and the sequenced JIT call. Summarized JIT calls are quantity-based or container-based, while sequenced JIT calls are order-based requests for supply in sequence. JIT calls are automatically send to the supplier. The supplier sends the components to the customer and the customer confirms the delivery when it is received. The system works for both internal as external suppliers. Two-stage production supply is also available in SAP. A supplier can deliver directly to the production line or to a supermarket that is located in the production plant. The newest SAP system (SAP S/4HANA) delivers 13 Fiori apps regarding material flow for 3 user personas: Production operator, Production planner and Production supervisor. The apps are displayed in Figure 10. The most relevant apps for JIT and JIS flow are explained.

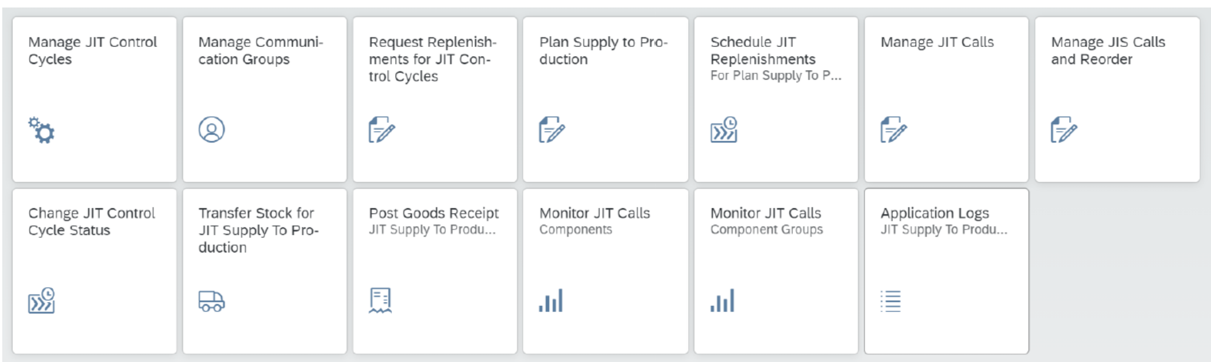


Figure 10: 13 SAP S/4HANA Fiori apps regarding JIT calls (SAP, 2021)

A control cycle ensures that the JIT calls are processed correctly. The control cycle is created and maintained with the app *Manage JIT Control Cycles* The control cycle includes a source, which could be a supplier or an internal storage location. Also a destination is included in the control cycle. The destination is always a production supply area. Within the control cycle, the user can manage and plan how the parts should be supplied to the line. JIT calls contain one or multiple call components. Each JIT call component is assigned to a call component group for processing. JIT call component groups could contain multiple components in case of sets or assembled modules requested through sequenced JIT calls. The materials within the component groups should be maintained in the control cycle. Via the *Request Replenishment App* a JIT call can be created manually. This action can also be executed for coupled parts. Components that are commonly requested together are coupled. All the coupled parts are delivered when a JIT call is placed for one of those components. Via the *Plan Supply App* a consumption-based or a demand-driven planning can be created. These two planning methods enable an automated creation of JIT calls. Consumption-based planning works with safety stock limits which are maintained in the control cycle master data. The demand-driven planning is based on a planning horizon which is also maintained in the control cycle master data. SAP S/4HANA also includes an app for reordering. If the production supply of a JIS component group was not successful or only parts of a component group arrived, the whole or only parts of the component group can be reordered with the *Manage JIS call and Reorder App.*

6.4. Future State

With the new insights from this chapter, the Assembly Production Control model is redesigned (see Figure 11 and Figure 12). The full process model can be found in the Appendix. In the ideal situation a couple of things are handled different:

The OPL and the ASSOR are merged. Section 4.6 already states that the possibility exists to integrate the ASSOR and the OPL into one system. Unfortunately, the required software is very costly and a lot of time needs to be invested in the implementation. Therefore, TP should consider if the improvement is worth the cost. Possibly, SAP could provide a solution when transferring the TP Mainframe to SAP.

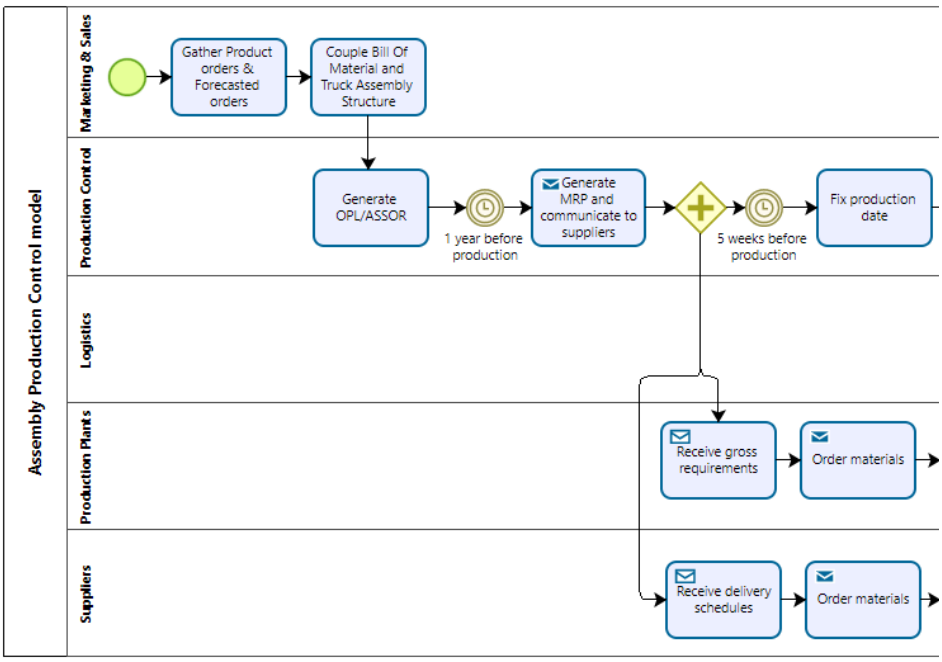


Figure 11: Future state Assembly Production Control model – Part 1

The day sequence of the truck plant is frozen 10 days before the assembly. As mentioned by Flexis in section 6.1.1, TP should freeze the day sequence of the assembly plant approximately 10 days before the assembly. Just as MAN, TP already uses a bucket system and a semi frozen zone in the Flexis system. The real frozen zone at TP is currently equal to 3 to 4 hours which is way too short. In order to ensure JIT and JIS deliveries by suppliers, a frozen zone of 10 days is absolutely necessary. The longer frozen zone makes it possible to even pull components from Eastern Europe, which is very cost efficient (see section 6.2). Flexis ensures that their updated APS system can handle the sequence calculations. Another possibility is to use a sequencing system developed by SAP.

The possibility to block a truck is removed from the model. Note that a blocking can still occur in a future Pearl Chain model. However, blockings on the deployment plan will become an exception. Currently, the occurrence of blockings is very common. So the amount of blockings has to be reduced drastically in the future. Reducing the amount of blockings will simplify the process because less process steps are needed. Potential shortages of components due to a small adjustment to the sequence can be internally resolved. Less blockings and a smaller duration of the blockings do not disturb the supply process. Blockings can be reduced by improving the assignment of workers and the supplier planning (see section 6.1.2). The SAP system supports pull deliveries and can give TP the ability to plan more meticulously (see section 6.3). An hour planning instead of a day planning could be very helpful. Next to this, it is vital to increase the First Time Right in the production of components and to improve the handling of rework (see section 6.2.2).

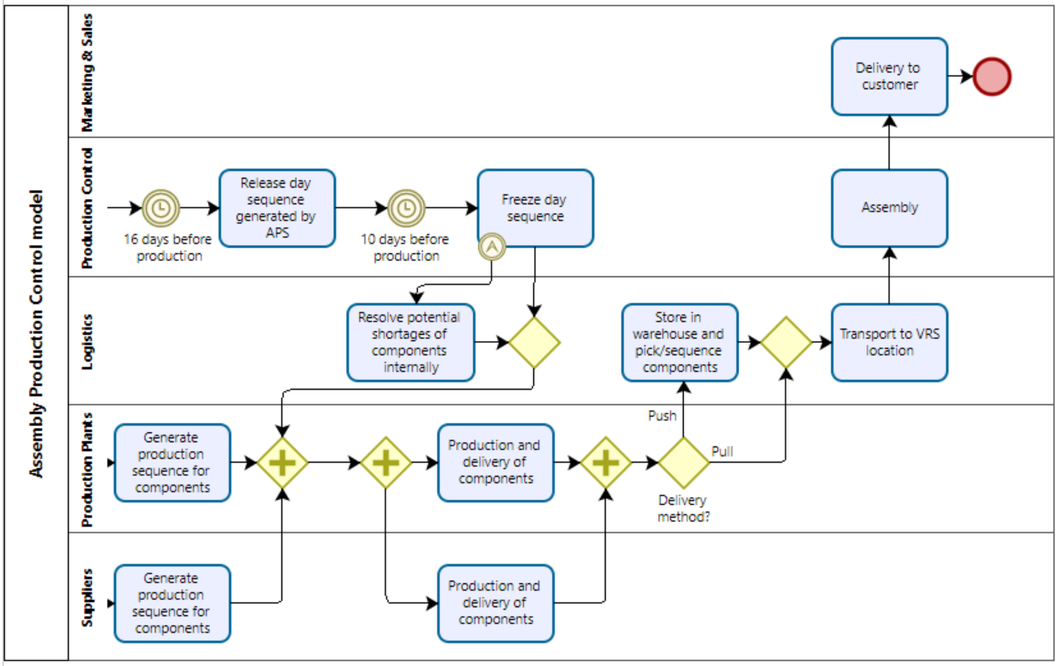


Figure 12: Future state Assembly Production Control model – Part 2

7. Assembly Plant Simulation - Current State

A simulation is built to investigate if a Pearl Chain model can lower buffers and save costs. First, the current production sequence within the assembly plant in the Netherlands is replicated and simulated. Thereafter, a future state Pearl Chain sequence is developed. Goal of the simulation is to investigate size differences in intermediate and supply buffers. The simulation is built with the simulation tool Plant Simulation which is developed by Siemens. First, the data preparation is discussed. Then, the current state simulation is elaborated, followed by the results.

7.1. Data

For the simulation of the current state sequence, data is used from 20 October 2020 to 9 April 2021. For every work station, production line and buffer, data is available. The work stations, production lines and buffers are all coupled to a VRS location. The data is summarised per VRS location. Every row represents a transport number which is coupled to a sales order. All the transport numbers have an input and output timestamp for the relevant VRS location. With this information it is possible to determine the current order sequence in the assembly plant. Half a year of data can give an extensive image of the buffer sizes in the assembly plant. The available data is loaded into the simulation model to recreate the order sequence of the period between October 2020 and April 2021. The relevant VRS locations for the simulation are given in sequential order of the production process (see Figure 6):

- *Inzetplan (=deployment plan)*
- *Hengelhoef*
- *Skids*
- *Buffer Skids*
- *Chassislijn 1*
- *Supply Buffer Axle*
- *Buffer Chassislijn*
- *Chassislijn 2*
- *Buffer Lakstraat*
- *Lakstraat*
- *Buffer Standbouw*
- *Eindlijn 1*
- *Buffer Eindlijn*
- *Eindlijn 2*
- *Supply Buffer Engine*
- *Supply Buffer Cabin*

Data contains flaws. Therefore, some data cleaning is performed first. Only orders generated after week 43 in 2020 are considered due to missing data for certain VRS locations before this week. Next to this, only orders which moved through the whole production line, according to the data, are used for the simulation. Ultimately, 20,437 records with matching transport numbers are used for every VRS location. A number of orders had missing input time stamps in the data. To solve this problem, the output time stamp of the previous VRS location for that specific transport number is located. By sorting all the orders on their input time stamp, the original sequence is recreated. The model is used to replicate the order sequence and simulate the production times based on average values. The timestamps in the data are not used to determine production times since they are error prone. Instead, average values are used to determine the production times. The tact time, the average line speed and the failure distributions are given in section 7.3.

The timestamps are error prone due to the fact that checking trucks in and out of the VRS location is a manual job which is done by the process operators. The scanning process is sensitive for errors. Operators can easily scan trucks in the wrong order. It will not lead to large displacements, but small displacements in the data are certainly possible. Displacements during the assembly can only happen by using the intermediate buffers. When a displacement occurs and the corresponding transport number has never entered an intermediate buffer, an error in the data is responsible for the displacement. It is impossible to find all these errors in the data. Therefore, the aim of the simulation is to replicate the sequence in the data as good as possible. The data sequence should not be replicated entirely because it contains errors. The next paragraph elaborates on the design of the simulation model.

7.2. Model Design

The simulation model is developed according to the flowchart in Figure 6. The layout of the model is given in Figure 13. It is important to note that sequence displacements can happen at two times. When a main component is not ready on time for a specific truck, that order is blocked on the deployment plan. This truck is not moving onto the assembly line yet. The assembly will start when all the main components are ready. The second possibility is that problems occur during the production. Disturbances can occur during the assembly or small components are not on stock. In that case, the trucks are sent into an intermediate buffer. For the research it is important to look into the two different possibilities of sequence displacements. Therefore, the simulation model contains the possibility to investigate sequence displacements before the assembly and during the assembly. Section 7.2.1 elaborates on disturbances during the assembly while section 7.2.2 discusses blockings before the assembly.

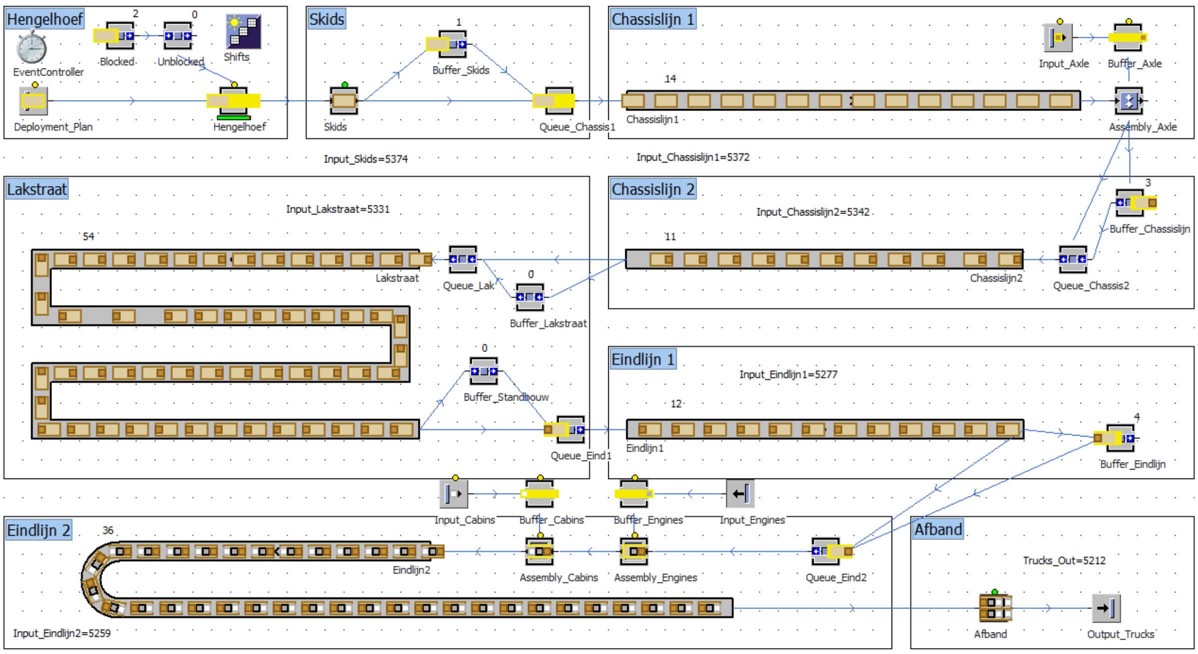


Figure 13: Layout of the simulation model

7.2.1. Disturbances during Assembly

Orders are moved from the deployment plan (*Inzetplan*) into the virtual buffer *Hengelhoef*. When analysing the intermediate buffers, the model uses the sequence data from *Hengelhoef* as input. The orders enter the model in the exact same order as they entered the assembly plant in reality. The supply buffers sizes are set very large. In that way, no blockings happen before the orders enter the assembly plant. This part of the analysis is purely focused on the intermediate buffers. For the routing of the orders, the data files mentioned in section 7.1 are used. If an order is present in a buffer data file, the order is sent to that specific buffer. A counter keeps track of the transport number that is next in line for every production line data file. Every time an order enters a production line, the counter adds one to the original value. When a transport number in the buffer is equal to the next transport number in line, that specific order can leave the buffer and is sent to the next production line. Queues before each production line ensure that the minimal pitch distance is used between every truck.

Because the checking in and out of trucks is sensitive to errors , orders with a small residence time in the buffer can be too late and are in that case not sent through to the next production line. Therefore a safety is built into the model in order to send late orders through to the next line. Without this safety the late orders will stay in the buffer for the rest of the simulation. That is certainly not desirable when analysing the results. Due to the uncertainty in the scanning process, the original sequence cannot be replicated entirely. However, the sequence can be replicated for a large part. Only small deviations appear in the replicated sequence.

A relatively high amount of trucks enters *Buffer Standbouw* in the data. Approximately 25% of the trucks enter this buffer. After doing some research into this phenomenon, the cause for the high result of buffer entries is found. Due to COVID-19 restrictions, certain actions could not be performed with at least 1.5 meters distance between every operator. Therefore, these specific trucks were placed in *Buffer Standbouw* to perform all necessary assemblies which were not possible at the production line. Because of this fact, the results of the current state simulation are not representative for the 'normal' situation. To solve this problem, the transport numbers are retrieved of the trucks which are moved to *Buffer Standbouw* because of COVID reasons. Subsequently, these transport numbers are deleted from the data file for *Buffer Standbouw*. From the beginning of 2021 till June 2021, approximately 4.3% of the trucks are moved to *Buffer Standbouw* because of reasons which had nothing to do with COVID. By sending less trucks into the buffer, a more representative current state situation is created.

When a truck enters a buffer, automatically the transport number and the input timestamp are written into a new data file. When this truck leaves the buffer, the exit timestamp is added. That makes it possible to investigate the residence time for every order. This action is executed at all of the buffers. Next to this, the same method is used when a truck enters the production at *Skids* and leaves the production line at *Eindlijn 2*. By doing this, the total lead time of every order can be analysed. *Afband* is left out because the order sequence changes very frequently in there. *Afband* contains different work stations with a complex routing process. Therefore it is left out of the scope for the simulation. No data regarding *Afband* is used or collected. By using the new written data files, it becomes possible to analyse the residence time at the intermediate buffers and the throughput time of the whole process. Additionally, data is created to analyse the intermediate buffer sizes over time. An analysis on intermediate buffer sizes requires a slightly different input than the analysis on supply buffer sizes. The analysis on supply buffer sizes is elaborated in section 7.2.2.

7.2.2. Blockings before Assembly

The supply buffers for main components (axle, engine and cabin) ensure that trucks can enter the assembly line at their scheduled time. In the analysis explained in section 7.2.1, the *Hengelhoef* sequence is used at the begin of the process. When analysing the supply buffers, the deployment plan sequence is loaded into the model at the begin of the process. Just as in reality, the deployment plan is adjusted when main components are missing. When a main component is not ready on time, the truck is blocked and it will not move onto the assembly line yet. With the help of VRS data, the main components enter the model in the same order as in reality. The assembly stations are used to assemble the main components onto the truck frame. The assembly of the axles happens at the end of *Chassislijn 1*. The assembly of the engines and the cabins happen at *Eindlijn 2*.

To analyse the supply buffers, the current average buffer sizes are tested. Ultimately, lower supply buffer sizes are tested in the future state simulation. When the main component for a certain order is not on stock, the matching transport number is blocked. All transport numbers with missing main components are blocked. When the missing main components arrive, the corresponding truck is unblocked and sent to *Hengelhoef.* That means the truck is ready for production. From then on, the orders are routed through the plant with the help of stochastic throughput rates and an average buffer time with a standard deviation. These parameters are calculated from the simulation of subsection 7.2.1. Data is exported in Microsoft Excel which can be used to calculate the throughput rates, the average buffer time and the standard deviation of the buffer time. The average buffer time is modelled with the log-normal distribution which is skewed to the right. This distribution resembles reality the best. The used throughput rates and buffer times are presented in the results section of the 'disturbances during assembly' analysis (section 7.4.1). Data is written into a table which is used to analyse the amount of blockings and the blocking time. This part of the analysis is limited to the supply buffers of the main components. The blocking of trucks causes a change in sequence. Because of these sequence changes it is not possible to simulate the actual supply buffers sizes and the actual intermediate buffers sizes in one analysis. A truck can be blocked due to various missing components. However, only the axles, engines and cabins are considered in the simulation because they are produced by TP itself and they account for the most delivery problems. Not all real-life blockings can be simulated but the blockings due to a missing axle, engine or cabin can. Because of this, the simulation model is restricted to one analysis at a time. An overview of the differences between the two models is given in Table 7.

Table 7: Differences between the two simulation models

	DISTURBANCES DURING ASSEMBLY	BLOCKING BEFORE ASSEMBLY
GOAL	Investigate intermediate buffer sizes and lead time	Investigate supply buffer sizes and amount of blockings
INPUT	*Hengelhoef* sequence	*Inzetplan* sequence
ROUTING	VRS data	Stochastic
OUTPUT	Average intermediate buffer occupation and average lead time	Amount of blockings under certain supply buffer sizes

7.3. Parameters

The assembly plant has two shifts: a morning and an evening shift. The morning shift starts at 7:05 and ends at 15:30. The evening shift starts at 15:35 and ends at 24:00. The two shifts also have 40 minutes break time. The total working time per day is 15.5 hours. Holidays and overtime are not taken into account. However, it is more interesting to analyse buffer occupation and lead time in terms of pure working time. Therefore, the working schedules are not considered during the analysis. A warmup period is used of 24 working hours. 1848 working hours are simulated for analysis purposes which is equal to 77 full working days.

According to the team leaders of the production lines, different line speeds are used in combination with different pitch distances. The pitch distance is the distance between the front sides of two trucks. Two areas are defined. Area 1 contains *Skids* to *Eindlijn 1* and area 2 contains *Eindlijn 2* and *Afband*. For area 1 the average line speed is 1.89 m/min and the average pitch distance is 8.4 meters. Area 2 has an average line speed of 1.67 m/min and an average pitch distance of 9.48. These values are calculated by taking the averages over the period between October 2020 and April 2021. The line speed, the line distance, the pitch distance and the capacity are given for all the production lines in Table 8. The line distance of the *Lakstraat* is in reality not 470.5 meters. A part of the *Lakstraat* has parallel lanes which are not built into the simulation. Therefore the line distance of *Lakstraat* is calculated by multiplying the pitch distance with the capacity. At the Skids station, an average tact time is used of 5 minutes and 30 seconds. This tact time in combination with the average line speeds and the exponential failures (Table 9) ensure a stable flow of truck orders through the assembly plant.

Table 8: Parameters per production line

PRODUCTION LINE	LINE SPEED (M/MIN)	LINE DISTANCE (M)	PITCH DISTANCE (M)	CAPACITY
CHASSISLIJN 1	1.89	115.7	8.4	14
CHASSISLIJN 2	1.89	97.8	8.4	12
LAKSTRAAT	1.89	470.4	8.4	56
EINDLIJN 1	1.89	102.4	8.4	13
EINDLIJN 2	1.67	339	9.48	36

In order to create a realistic simulation, the failures of the production lines are also simulated. Failures are given an exponential distribution. The exponential distribution defines a process in which events occur continuously and independently at a constant average rate. These characteristics are familiar for the failure distribution of the production lines. Each production line has a different failure distribution. The Mean Time To Failure (MTTF) and the Mean Time To Repair (MTTR) are also calculated by taking the average values over the period between October 2020 and April 2021. *Chassislijn 1* and *Chassislijn 2* are directly connected, therefore they have the same failure distribution. The MTTF and the MTTR values are given in Table 9.

Table 9: MTTF and MTTR per production line

PRODUCTION LINE	MEAN TIME TO FAILURE	MEAN TIME TO REPAIR
CHASSISLIJN 1	55:30	3:11
CHASSISLIJN 2	55:30	3:11
LAKSTRAAT	5:57:00	19:18
EINDLIJN 1	1:54:00	3:13
EINDLIJN 2	58:00	1:58

The order sequence is the simulated variable. The different future state scenarios are explained in section 8.1. The order sequence influences the amount of blocked trucks, the sizes of the supply and intermediate buffers, the waiting time in the buffers and the average throughput time. Therefore, the differences in blockings, buffer sizes, waiting time and throughput time are investigated in the rest of the report. The parameters explained in this section are used for both the current state as the future state simulation. The following paragraph presents the results of the current state simulation.

7.4. Results Current State

The following section shows the results of the current state simulation. Section 7.4.1 presents the results of the 'disturbances during assembly' analysis and section 7.4.2 gives the results of the 'blockings before assembly' analysis.

7.4.1. Intermediate Buffers & Lead Time

After analysing the data, the TP sequence score at *Eindlijn 2* is equal to 46.63% in comparison with the *Hengelhoef* and 25.86% when compared with the delivery plan (=*Inzetplan*). The relative sequence score between *Inzetplan* and *Hengelhoef* is equal to 33.25%. The sequence scores from the simulation model deviate slightly. *Hengelhoef* vs *Eindlijn 2* scores a bit better in the simulation model but this is certainly possible. Paragraph 7.1 already states that the data sequence can derive slightly from reality due to errors in data collection. The simulation model tries to replicate the data sequence as good as possible. However, it is simply not possible to replicate the data sequence entirely due to errors in the data. The simulation model has a better sequence score because negative displacements can happen in the data but not in the simulation model. For example, some cases in the data are moved into an intermediate buffers but they should already have been on the next production line according to the data. In reality, this is not possible and therefore it is also not possible in the simulation model. The sequence scores of the data and the simulation model are given in Table 10.

Table 10: Sequence scores of the data vs the simulation model

VRS LOCATIONS	DATA	SIMULATION
INZETPLAN VS HENGELHOEF	33,25%	-
INZETPLAN VS EINDLIJN 2	25,86%	26.31%
HENGELHOEF VS EINDLIJN 2	38,23%	46.63%

Table 11 displays the stochastic throughput rates and the average buffer time of the developed model. The throughput rates at the end of the process, at B*uffer Standbouw* and *Buffer Eindlijn,* are particularly lower than the throughput rates at the begin of the process. The throughput rate shows which part of the orders moves through the assembly process without visiting that particular buffer. The percentage in the next right column gives the percentage of orders that moves into a particular buffer and the most right column gives the average residence time of that buffer in hours. In total, 88.389% of the orders flow through the process without visiting any intermediate buffers. 11.611% of the orders visit an intermediate buffer. The weighted average residence time for all intermediate buffers is equal to 4.60 hours. The amount of orders that flow through each buffer are taken into account when calculating this average number. The corresponding standard deviations are also presented in the table. The throughput rates correspond exactly to the used data. Unfortunately, the average residence time could not be compared with the data because the simulation uses pure working time while the data uses 'normal' time.

Table 11: Flow percentages and residence time per intermediate buffer

BUFFER	THROUGHPUT RATE (%)	ORDERS INTO BUFFER (%)	AVERAGE RESIDENCE TIME (HOURS)	STANDARD DEVIATION (HOURS)
SKIDS	99.357	0.643	5.66	7.85
CHASSISLIJN	98.447	1.553	5.68	6.44
LAKSTRAAT	98.996	1.004	4.19	5.40
STANDBOUW	95.887	4.113	3.47	7.29
EINDLIJN	95.702	4.298	5.24	7.38
OVERALL	**88.389**	**11.611**	**4.60**	**7.08**

Figure 14 shows the distribution of the different intermediate buffer sizes. *Buffer Skids* and *Buffer Lakstraat* are most of the time empty while *Buffer Chassislijn* contains mostly one truck order. The sizes of *Buffer Standbouw* and *Buffer Eindlijn* vary a lot. Most of the time, these buffers contain more than one order. This can also be seen in Table 12. *Buffer Skids* and *Buffer Lakstraat* have a relatively low buffer occupation. *Buffer Chassislijn* scores a bit higher with an average buffer occupation of approximately one order. Buffer Standbouw has an average buffe occupation of approximately 1.6 orders. Note, all the orders that are placed in Buffer Standbouw due to COVID reasons are excluded from the data. So the real buffer occupation of Buffer Standbouw lies a lot higher. However, the numbers that are presented give a realistic insight of what the average buffer occupation would be when no COVID measures are present. *Buffer Eindlijn* has the highest average buffer occupation. A possible explanation could be that two main components (engine and cabin) are assembled on *Eindlijn 2* after this buffer. So if there are issues with any of these components and the assembly already started, the truck is placed in *Buffer Eindlijn*.

Table 12: Average buffer occupation per intermediate buffer

BUFFER	AVERAGE BUFFER OCCUPATION
SKIDS	0.4027
CHASSISLIJN	0.9735
LAKSTRAAT	0.4659
STANDBOUW	1.5659
EINDLIJN	2.3922
TOTAL	**5.8002**

An average lead time per order from *Skids* to *Eindlijn 2* is retrieved of **12.74** working hours. The distribution of the lead time is given in Figure 15, sorted from low to high. About 20,000 orders are considered during this research. It is visible that the majority of these orders has a lead time below the 20 hours. However, a minority of approximately 400 orders rises above the 20 hours. Several outliers are present which rise until 120 working hours. The next paragraph presents the method and the results of the 'blockings before assembly' analysis. Different future state 'Pearl Chain' scenarios for this analysis are presented in section 8.1.1.

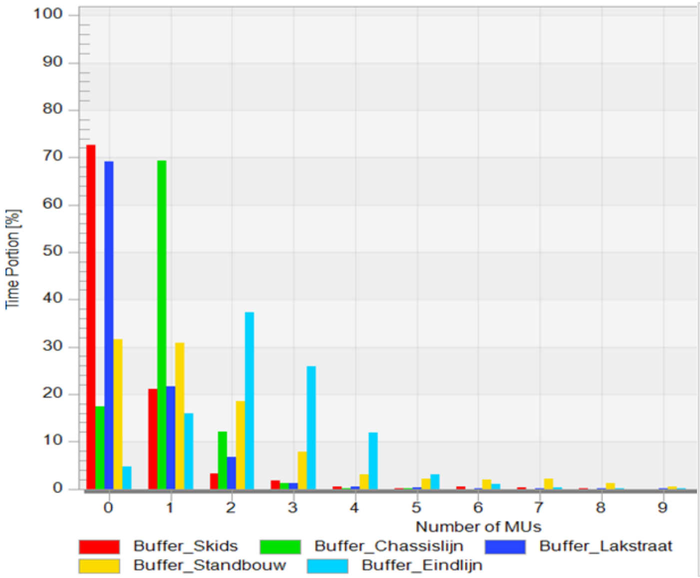


Figure 14: Distribution of intermediate buffer sizes

Figure 15: Distribution of the lead time in hours

The model is validated by using the parameters from Table 11 in a new stochastic model and getting the same results in terms of sequence score, total buffer occupation and average lead time as in the original model. The goal is to use the parameters in Table 11 for the analysis on the supply buffers of the current state process. Next to this, stochastic models are also used for the future state simulations. The results of the validation runs are presented in Table 13. One can see from the results that the sequence scores, the total average buffer occupation and the average lead time are similar for all the validation runs. The average values of the validation runs are very close to the results of the current state simulation. Therefore, the stochastic model can be used for other purposes during the rest of the research. The same stochastic model is used in subsection 7.4.2. The model is also used for the future state simulations. Only different parameters are inserted.

Table 13: Results of the validation runs

VALIDATION	SEQUENCE SCORE	BUFFER OCCUPATION	LEAD TIME (HOURS)
RUN 1	46.04%	5.8110	12.71
RUN 2	47.17%	5.4398	12.92
RUN 3	46.07%	5.8399	12.96
RUN 4	46.90%	5.6423	12.88
RUN 5	46.12%	5.7901	12.74
RUN 6	45.90%	5.9676	12.83
RUN 7	46.07%	6.0265	12.94
RUN 8	46.04%	5.8280	12.82
RUN 9	46.49%	5.6466	12.92
RUN 10	46.78%	5.6011	12.95
AVERAGE	**46.36%**	**5.7593**	**12.87**
CONFIDENCE	**1.27%**	**0.5867**	**0.25**

7.4.2. Supply Buffers vs Blockings

A couple of buffer sizes are tested for the main components. Before truck orders move into the *Hengelhoef*, the availability of all the main components is checked. If a component is not available the order is blocked and it will not move to the *Hengelhoef* yet. Whether a truck order is blocked is strongly dependent on the buffer sizes of the main components. In this experiment, the size of the buffers is equal to the amount of main components which are released for truck assembly. So the point in time where a main component is released for truck assembly is used as reference point. For the cabin, this reference point lies from the delivery buffer in Belgium (337 cabins on average) to the supply buffer in the Netherlands (33 cabins on average). The axle assembly happens early in the process. Therefore, axles are released when they are in the supply buffer in the Netherlands (155 axles on average). Engines are released for truck assembly when they are in the last production phase. The engine is not ready yet but the possibility that the engine arrives too late at the assembly line is very small in that case. The supply buffer is then equal to the amount of components in the last production phase (107 engines on average) plus the supply buffer in the Netherlands (96 engines on average). The average buffer sizes from begin 2020 to mid-2021 are displayed in Table 14.

Table 14: Average supply buffer sizes for the current state simulation

BUFFER SIZE	AXLES	ENGINES	CABINS
CURRENT SIZE	155	107+96=202	337+33=370

In Table 15, the sequence scores are displayed for the supply of the main components vs the deployment plan (=*Inzetplan*) and *Hengelhoef*. The supply of the axles clearly scores better on the *Inzetplan* than the engine and cabin supply. That is because the axle supply sequence is currently based on the *Inzetplan* while the engine and cabin supply sequence are dependent from the production sequence in the engine/cabin plant. Since the axles are assembled early in the assembly process, the release point lies later in the process. Because of that, the sequence score automatically improves. The late release gives TP Belgium time to sequence the axles in the right order. TP Belgium can deliver the axles in such a good sequence because they have an average of 361 axles on stock or on transport. All these axles are not taken into account when releasing truck orders for production. Only axles in the Netherlands are considered for the release of a truck order. Therefore, the axles in Belgium are not considered during this analysis. It could be interesting to investigate TP Belgiums axle delivery buffer in further research. The engine plant delivers a reasonable sequence score because there is only a small engine buffer present. The sequence score of the cabin plant on the other hand is a lot lower. That is possible because a couple of steps are still necessary to get the cabin in the Netherlands.

Table 15: Sequence scores of the supply of main components

	AXLE	ENGINE	CABIN
INZETPLAN	68.06%	52.29%	19.21%
HENGELHOEF	33.08%	36.47%	19.85%

Table 16 presents the amount of blockings for the current state simulation. Approximately 20,000 truck orders are used for analysis purposes. So in the current situation, approximately 5% of the truck orders are blocked before the assembly. The average duration of a blocking is equal to 17.74 working hours.

Table 16: Amount of blockings and the average lead time for the current state simulation

BUFFER SIZE	AMOUNT OF BLOCKINGS	AVERAGE DURATION (HOURS)
CURRENT SIZE	1077	17.74

It is interesting to know why these blockings occurred. Table 17 gives the amount of orders that are blocked due to a specific missing main component. Remarkable is that missing axles do no lead to a lot of blockings. The high delivery buffer in Belgium could be a good explanation. Engine and cabin supply both account for a lot of blockings. The release of these components is currently directed by the production sequence. Therefore a lot of blockings occur. However, it is not possible to keep directing the supply based on the production sequence when TP wants to implement a Pearl Chain. Not the production sequence should be leading for the supply of the main components but the *Inzetplan* sequence should be leading. Therefore, it is important to conduct these blocking tests based on the *Inzetplan* sequence.

Table 17: The amount of missing main components which caused blockings

BUFFER SIZE	AXLE	ENGINE	CABIN
CURRENT SIZE	30	349	752

For the future state simulation, a more stable flow of main components based on the *Inzetplan* is created. The goal is to compare the amount of blockings in the current state simulation with the amount of blockings in a future state ‘Pearl Chain’ simulation.

8. Assembly Plant Simulation – Future State

This chapter is used to develop a future state simulation in Plant Simulation. First, the future state model is elaborated. After that, the results of the experiment are presented. At the end, the current state results are compared with the future state results. The findings and cost savings that can be derived from these results are discussed.

8.1. Model Design

The goal is to create a future state Pearl Chain in Plant Simulation and to compare this Pearl Chain model with the current state model. A Pearl Chain has a more stable order sequence than TP has now. So the order sequence is the variable that will be simulated. On one side, TP needs to provide a more stable flow of main components (axle, engine, cabin). On the other side, TP needs to provide a more stable flow of trucks through the assembly plant. When a more stable flow can be maintained, the supply buffers can be lowered and the intermediate buffers will eventually lower too. Section 8.1.1 discusses the future state simulation of the truck flow during assembly. Section 8.1.2 elaborates on the future state simulation of the main components flow before assembly.

8.1.1. Flow of Trucks during Assembly

The current throughput rates of trucks through the assembly line are displayed in the column 'Current State' of Table 18. Based on these current throughput rates, a couple of scenarios are designed. The throughput rates of the production lines are increased in order to create a more stable order flow which ultimately resembles a Pearl Chain. Three scenarios are used to gradually increase the overall throughput rate to 99%. A throughput rate of 99% means that 99% of the orders move through the assembly line without visiting an intermediate buffer. To realise this throughput rate in real-life, time and money should be invested in process optimisation. MAN already showed that S*cenario 3* is feasible.

Table 18: Throughput rates per buffer (current vs future state scenarios)

BUFFER	*CURRENT STATE* (%)	*SCENARIO 1* (%)	*SCENARIO 2* (%)	*SCENARIO 3* (%)
SKIDS	99.357	99.5	99.5	99.8
CHASSISLIJN	98.447	99.5	99.5	99.8
LAKSTRAAT	98.996	99.5	99.5	99.8
STANDBOUW	95.887	96.25	98.25	99.8
EINDLIJN	95.702	96.25	98.25	99.8
OVERALL	**88.389**	**91**	**95**	**99**

In a Pearl Chain, not only the throughput rate is important. Also the size of the deviation is of interest. In other words, the residence time of a truck in the intermediate buffer is also very important. The residence time determines the size of the sequence deviation. If the residence time is too long, more trucks should be moved forward in the sequence. The possibility then rises that essential components are missing for the trucks that are moved forward. From the current state simulation (Table 11) one can find the average residence time per intermediate buffer. All the different scenarios are tested with the current average residence time. To see if the residence time is a big influencer, all the scenarios are also tested with half of the average residence time per intermediate buffer. The corresponding standard deviation is also divided by two. With the help of the previously mentioned scenarios, a couple of Pearl Chain degrees are simulated. The throughput rates and the average residence times are easily inserted in Plant Simulation. The goal is to investigate the influence of the order sequence on the average intermediate buffer occupancy and the average lead time. Subsequently, cost savings are calculated. The results of this analysis are presented in section 8.2.1.

8.1.2. Flow of Main Components before Assembly

The current state flow of main components deviates from the deployment plan. In the ideal situation, the flow of main components is exactly the same as the deployment plan. However, in reality this is hard to reach. For a future Pearl Chain scenario, a gradual increase of stability in the main components flow is implemented. The deployment plan is randomly permutated to gradually increase the sequence stability. The sequence stability includes the amount of deviations and the length of the deviations. Different sequences are generated with the help of Plant Simulation. These sequences are all tested on their sequence performance. Three scenarios are developed with gradually increasing supply sequence performances. For the first scenario, the cabin sequence is improved to the height of the engine sequence. For the second scenario, the cabin an engine sequence are both improved to be as good as the axle sequence. The third scenario improves the supply sequence of the three main components even more to approximately 85%. These scenarios are feasible as long as enough time and money is invested in the optimalisation of the supply sequences. The current state and the three future state scenarios are given in Table 19.

Table 19: The sequence scores of the current state and the future state scenarios of the main component supply

SCENARIO	AXLE	ENGINE	CABIN
CURRENT STATE	68.06%	52.29%	19.21%
SCENARIO 1	68.06%	52.29%	46.79%
SCENARIO 2	68.06%	70.59%	65.96%
SCENARIO 3	86.33%	83.98%	82.60%

The buffers for engines and cabins should be at least equal to 136 (the capacity of *Hengelhoef* to *Eindlijn 1*) and the axle buffer should be at least equal to 55 (the capacity of *Hengelhoef* to *Chassislijn 1*). This rule applies because orders are not moved to *Hengelhoef* when a main component is missing. On top of the minimum buffer sizes, additional buffer is needed to account for sequence deviations. *Buffer size 3* uses an additional buffer size of 50 orders for the axle, engine and cabin buffer. The current order sequence needs at least these approximate buffer sizes in order to produce all orders. Otherwise, the model keeps blocking incoming orders at a certain point because no orders can be found with available components. A gradual decrease is implemented from the *current buffer size* to *buffer size 3*. The experimental supply buffer sizes for the current state simulation are displayed in Table 20. To model the flow after *Hengelhoef*, the parameters presented in Table 11 are used.

Table 20: Experimental supply buffer sizes for the future state simulation

BUFFER SIZES	AXLES	ENGINES	CABINS
CURRENT SIZE	155	107+96=202	337+33=370
BUFFER SIZE 1	138	196	309
BUFFER SIZE 2	122	191	247
BUFFER SIZE 3	105	186	186

The three scenarios are loaded into the simulation model. The goal is to investigate the differences in amount of blockings. The future state scenarios are compared with each other and with the current state. The results of this analysis are presented in section 8.2.2.

8.2. Results

This paragraph is used to present the results of the future state simulations. The developed future state scenarios are compared with each other and with the current state results. Section 8.2.1 gives the results of the analysis on intermediate buffers and lead time. Section 8.2.2 presents the results of the analysis on supply buffers and blockings.

8.2.1. Intermediate Buffers & Lead Time

In Table 21, the average buffer occupation is displayed per scenario with the current average residence time. Table 22 represents the average buffer occupation with half of the average residence time. The standard deviation is also halved. *Scenario 1* makes it possible to reduce the average buffer occupation by approximately 1.4 truck. *Scenario 2* reduces the buffer sizes by approximately 3.2 trucks while *Scenario 3* saves 5.2 buffer places. With the current throughput rates and half the residence time, the total average buffer occupation is equal to approximately 2.9 trucks. With half the residence time, *Scenario 1* decreases the total average buffer occupation to 2.2 trucks. *Scenario 2* can reduce the buffer occupation of *Scenario 1* by another 0.9 truck. *Scenario 3* with half the residence time uses only 0.3 truck in the buffers. When the residence time is halved, the average buffer occupation is also halved. However, it is not necessarily more profitable to lower the residence time. When the throughput rates are increased and less trucks move into the buffer, TP can also save handling costs.

Table 21: Average buffer occupation per scenario with current average residence time

BUFFER	*SCENARIO 1*	*SCENARIO 2*	*SCENARIO 3*
SKIDS	0.3016	0.3019	0.1359
CHASSISLIJN	0.3167	0.3169	0.1433
LAKSTRAAT	0.2629	0.2629	0.1003
STANDBOUW	1.4757	0.6904	0.0996
EINDLIJN	2.0560	1.0083	0.1120
TOTAL	**4.4131**	**2.5805**	**0.5910**

Table 22: Average buffer occupation per scenario with half of the average residence time

BUFFER	*CURRENT THROUGHPUT*	*SCENARIO 1*	*SCENARIO 2*	*SCENARIO 3*
SKIDS	0.1977	0.1509	0.1506	0.0678
CHASSISLIJN	0.5070	0.1635	0.1638	0.0719
LAKSTRAAT	0.2422	0.1318	0.1320	0.0501
STANDBOUW	0.7886	0.7379	0.3451	0.0500
EINDLIJN	1.1723	1.0269	0.5044	0.0562
TOTAL	**2.9077**	**2.2111**	**1.2958**	**0.2960**

The sequence scores per scenario and the average lead time are displayed in Table 23. It is easy to say that a higher sequence score will improve the average lead time. A higher sequence score means less deviations. Therefore, less trucks are moved into an intermediate buffer and the average lead time will decrease. An overall throughput rate improvement of 3 to 4 percent will lead to a lead time reduction of approximately 0.2 hours with the current residence time. With half the residence time, a reduction of approximately 0.1 hours can be achieved. Scenario 3 could realise an average lead time reduction of more than half an hour. Subsection 8.2.2 presents the results of the future state analysis on supply buffers.

Table 23: Sequence score and average lead time per scenario

SCENARIO	SEQUENCE SCORE	AVERAGE LEAD TIME (HOURS)
SCENARIO 1 – CURRENT RESIDENCE TIME	52.65%	12.54
SCENARIO 2 – CURRENT RESIDENCE TIME	70.74%	12.35
SCENARIO 3 – CURRENT RESIDENCE TIME	92.81%	12.13
CURRENT THROUGHPUT – HALF RESIDENCE TIME	65.93%	12.44
SCENARIO 1 – HALF RESIDENCE TIME	75.02%	12.35
SCENARIO 2 – HALF RESIDENCE TIME	90.44%	12.19
SCENARIO 3 – HALF RESIDENCE TIME	96.08%	12.10

8.2.2. Supply Buffers vs Blockings

The current state supply sequence scores are gradually increased in order to investigate the differences in amount of blockings. Table 24 and Table 25 present the results for the first future state scenario where the cabin supply sequence is improved to be almost as good as the engine sequence.

Table 24: Blockings per supply buffer sizes for Scenario 1

BUFFER SIZES	AMOUNT OF BLOCKINGS	AVERAGE DURATION (HOURS)
CURRENT SIZE	387	12.96
BUFFER SIZE 1	486	11.84
BUFFER SIZE 2	664	10.66
BUFFER SIZE 3	1278	7.98

Table 25: The amount of missing main components which caused blockings per buffer size for Scenario 1

BUFFER SIZES	AXLE	ENGINE	CABIN
CURRENT SIZE	30	310	64
BUFFER SIZE 1	33	338	134
BUFFER SIZE 2	40	368	279
BUFFER SIZE 3	50	443	825

Subsequently, the cabin and engine sequence are both improved to be approximately as good as the axle sequence. The results are displayed in Table 26 and Table 27. Just as in S*cenario 1*, the amount of blockings and the average duration of the blockings steadily descend.

Table 26: Blockings per supply buffer sizes for Scenario 2

BUFFER SIZES	AMOUNT OF BLOCKINGS	AVERAGE DURATION (HOURS)
CURRENT SIZE	287	10.53
BUFFER SIZE 1	346	9.54
BUFFER SIZE 2	444	8.52
BUFFER SIZE 3	806	6.35

Table 27: The amount of missing main components which caused blockings per buffer size for Scenario 2

BUFFER SIZES	AXLE	ENGINE	CABIN
CURRENT SIZE	29	251	8
BUFFER SIZE 1	33	288	26
BUFFER SIZE 2	37	317	91
BUFFER SIZE 3	46	360	412

Then, all the three supply sequences are improved to a sequence score of approximately 85%. And again the amount of blockings and the average duration decrease. The results are visible in Table 28 and Table 29. Remarkable is that the amount of blockings caused by missing axles increased from *Scenario 2* to S*cenario 3*. However, the amount of blockings in *Scenario 3* is similar to the amount of blockings caused by engines or cabins. From that, the following can be concluded: the current axle supply sequence has a low amount of blockings for its sequence score. So the current axle sequence probably has less deviations but the size of the deviations is bigger. Section 8.3 is used to elaborate on the findings and the possible cost savings.

Table 28: Blockings per supply buffer sizes for Scenario 3

BUFFER SIZES	AMOUNT OF BLOCKINGS	AVERAGE DURATION (HOURS)
CURRENT SIZE	167	7.16
BUFFER SIZE 1	214	6.49
BUFFER SIZE 2	280	5.98
BUFFER SIZE 3	489	4.90

Table 29: The amount of missing main components which caused blockings per buffer size for Scenario 3

BUFFER SIZES	AXLE	ENGINE	CABIN
CURRENT SIZE	35	129	6
BUFFER SIZE 1	58	151	9
BUFFER SIZE 2	84	172	34
BUFFER SIZE 3	139	194	179

8.3. Findings

The following section compares the results of the current and the future state simulations. Findings are derived and presented. At the end, cost savings are determined. The cost savings are based on possible inventory reductions and savings on handling costs.

8.3.1. Disturbances during Assembly

Table 30 gives the total average buffer occupation for each scenario. Figure 16 visualises these results in a graph. Mark that the COVID related buffer visits to *Standbouw* are left out of the analysis. In section 8.3.3, cost savings based on the potential buffer reduction are calculated.

Table 30: Total average buffer occupation per scenario

	CURRENT RESIDENCE TIME	HALVED RESIDENCE TIME
CURRENT STATE	5.8002	2.9077
SCENARIO 1	4.4131	2.2111
SCENARIO 2	2.5805	1.2958
SCENARIO 3	0.5910	0.2960

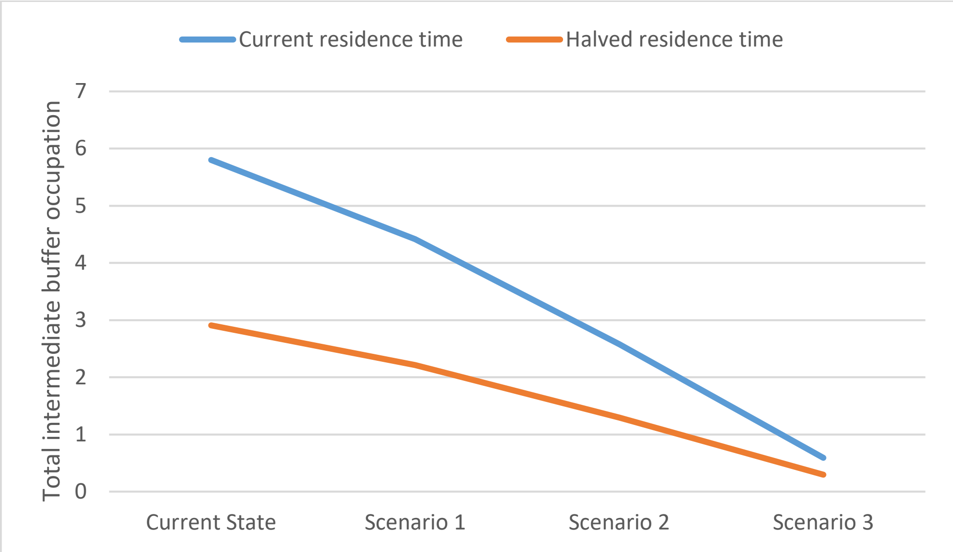


Figure 16: Total average buffer occupation per scenario

In addition, savings on handling cost can be achieved. These are dependent on the overall outflow rate at *Buffer Chassislijn*. Each time a truck is moved to *Buffer Chassislijn*, a gap on the *Chassislijn* originates. Because of that, the time of operators is wasted due to a lack of work. This does not happen at *Buffer Lakstraat* because the *Lakstraat* has a high capacity and needs a relatively low amount of workers. *Buffer Standbouw* and *Buffer Eindlijn* mostly contain more trucks which can be used to fill the gap that arises. For the future state scenarios, it is important that the moving in and out of trucks happens as cost efficient as possible at these two buffers. That is to prevent extra handling costs. *Buffer Skids* lies before the production line so that buffer does also not lead to a gap. A gap on the line only originates due to *Buffer Chassislijn.* Empty space arises on *Chassislijn 2* after moving the truck to the buffer and empty space on *Chassislijn 1* is needed to move the truck back on the line. With the outflow rates of *Buffer Chassislijn*, it is possible to determine cost savings per scenario. TP produced 37,580 trucks in 2020. The throughput and the outflow at *Buffer Chassislijn* is presented in Table 31. The numbers are presented in percentages and in trucks per year.

Table 31: Throughput and outflow per scenario for Buffer Chassislijn

FLOW	*CURRENT STATE*	*SCENARIO 1 & 2*	*SCENARIO 3*
THROUGHPUT (%)	98.447%	99.5%	99.8%
THROUGHPUT (TRUCKS)	36,996	37,392	37,505
OUTFLOW (%)	1.553%	0.5%	0.2%
OUTFLOW (TRUCKS)	584	188	75

8.3.2. Blockings before Assembly

The amount of blockings per scenario are presented in Table 32 and visualised in Figure 17. Note that *buffer size 1* to *buffer size 3* are not feasible for the current state sequence and therefore they are not tested. The current state cabin sequence does not allow a low cabin buffer size because at a certain point no available truck order can be found. All orders are blocked in that case. With the current state supply, it is absolutely not profitable to lower the supply buffers. Lower buffer sizes will only lead to more blockings. On the other hand, the future state scenarios all have a certain cost saving in terms of buffer reduction. These possible cost savings are calculated in section 8.3.3.

Table 32: Amount of blockings per scenario

	CURRENT STATE	SCENARIO 1	SCENARIO 2	SCENARIO 3
CURRENT SIZE	1077	387	287	167
BUFFER SIZE 1	-	486	346	214
BUFFER SIZE 2	-	664	444	280
BUFFER SIZE 3	-	1278	806	489

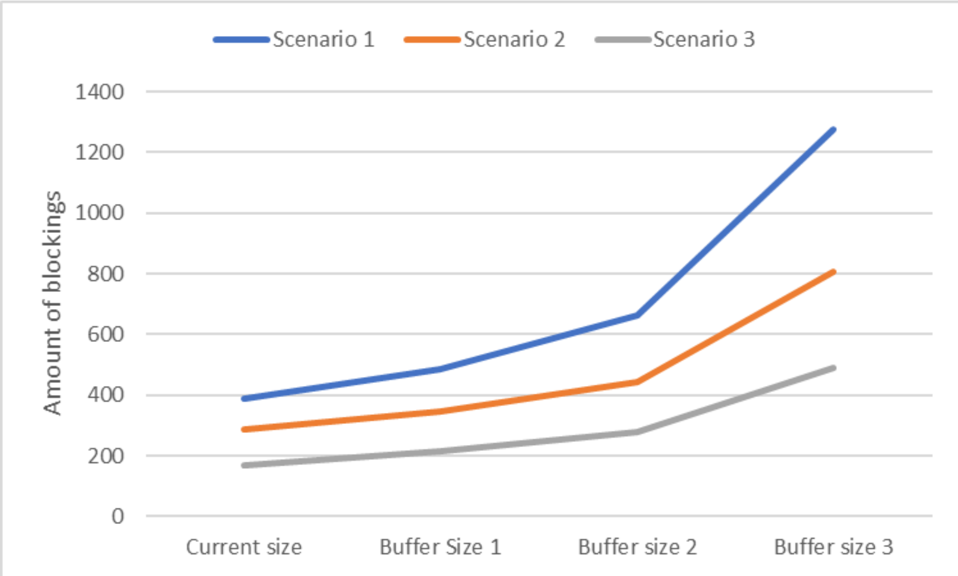


Figure 17: Amount of blockings per scenario

8.3.3. Cost savings

All the potential cost savings are calculated in this section. Three possible cost savings are distinguished. First, the possible cost savings on handling costs for *Buffer Chassislijn* are calculated. Followed by the potential cost savings on inventory reduction of the intermediate buffers and the supply buffers.

When a truck is moved into *Buffer Chassislijn*, a five minute (=tact time) gap on the production line arises. Because of that, the time of operators is wasted due to a lack of work. With the outflow rates in 8.3.1, it is possible to determine the cost savings per scenario. The cost for moving one truck to *Buffer Chassislijn* is equal to the wasted operator time multiplied with the hourly costs of an operator. The developed simulation from chapter 7 produces 170 trucks per day. An approximate amount of 235 operators are needed per day to produce this output on *Chassislijn 1* and *2* combined. TP has two shifts so *235/2=117.5* operators that are needed on *Chassisijn 1* and *2* per shift. Moving a truck into *Buffer Chassislijn* corresponds to the following amount of wasted time: *117.5 operators*5 minutes=587.5 minutes=9.8 hours*. The hourly rate for an operator is equal to €42.10. Therefore, the costs for moving one truck into *Buffer Chassislijn* are equal to *9.8*42.10=**€412.58***. With the outflow rates from Table 31, the yearly handling cost savings are calculated for each scenario in Table 33.

Table 33: Yearly cost savings on handling by skipping Buffer Chassislijn

SCENARIO	YEARLY HANDLING SAVINGS
SCENARIO 1 & 2	*(584-188)*412.58=**€163,381.68***
SCENARIO 3	*(584-75)*412.58=**€210,003.22***

Table 34 give the average book value per components. These values are used to calculate the total inventory reduction in euros per scenario. Subsequently, a Lean Six Sigma rule is applied. For balance reduction of raw materials or work in progress a cost saving of 10% of the book value is used. The 10% in cost savings consist of three kind of savings. Savings on storage costs, hazard costs and lost interest costs. In other words, less money will be used to pay for warehouses. Less inventories means less risk on defects due to accidents. And if less money is invested in inventories, more money can be invested in high interest goals. These cost savings are estimated per inventory reduction.

Table 34: Average book value per component

COMPONENT	AVERAGE BOOK VALUE (€)
TRUCK ASSEMBLY	61,406
CABIN	14,061
ENGINE	18,646
AXIS ASSEMBLY	5,105

With the average buffer occupation from Table 30, the potential inventory reduction of the intermediate buffers is calculated per scenario. Subsequently, the 10% cost savings are calculated. The savings are presented in Table 35.

Table 35: Cost savings on inventory reduction of the intermediate buffers

	CURRENT RESIDENCE TIME	HALVED RESIDENCE TIME
CURRENT STATE	-	2.8925*61,406*10%=**€17,761.69**
SCENARIO 1	1.3871*61,406*10%=**€8,517.63**	3.5891*61,406*10%=**€22,039.23**
SCENARIO 2	3.2197*61,406*10%=**€19,770.89**	4.5044*61,406*10%=**€27,659.72**
SCENARIO 3	5.2092*61,406*10%=**€31,987.61**	5.5042*61,406*10%=**€33,799.09**

Also an inventory reduction can be achieved for the supply buffers. With the buffer sizes in Table 20 and the book values in Table 34, the inventory reduction per buffer size is calculated. The 10% rule is again used to calculate the potential cost savings. Important note is that each buffer size corresponds to a certain number of blockings in combination with different scenarios. For example, suppose TP's goal is to keep the amount of blockings below 500 (data is used of approximately half a year). In that case, *Buffer Size 1* is suitable for *Scenario 1*. *Buffer Size 2* is suitable for *Scenario 2* and *Buffer Size 3* is suitable for *Scenario 3*.

Table 36: Cost savings on inventory reduction of the supply buffers

	BUFFER SIZE 1	***BUFFER SIZE 2***	***BUFFER SIZE 3***
AXLE	*(155-138)*5,105*10%=* ***€8,678.50***	*(155-122)*5,105*10%=* ***€16,846.50***	*(155-122)*5,105*10%=* ***€16,846.50***
ENGINE	*(202-196)*18,646*10%= €11,187.60*	*(202-191)*18,646*10%=* ***€20,510.60***	*(202-186)*18,646*10%=* ***€29,833.60***
CABIN	*(370-309)*14,061*10%= €85,772.10*	*(370-247)*14,061*10%=* ***€172,950.30***	*(370-186)*14,061*10%=* ***€258,722.40***
TOTAL	***€105,638.20***	***€210.307.40***	***€305,402.50***

So overall, TP could gain a couple of savings by reducing the intermediate buffers and the supply buffers. Next to this, some yearly handling costs could be saved at *Buffer Chassislijn*. Chapter 9 elaborates on the savings that could be made if regular components are delivered in sequence to the assembly plant.

9. Savings by Sequencing

The Pearl Chain method can not only decrease the sizes of intermediate and supply buffers. It can also decrease the inventories of regular components. This chapter is used to indicate what the inventory savings for certain product groups can be when a stable sequence is maintained and more components are delivered in sequence. It is impossible to do a calculation for all product groups within the given timeframe. Therefore, three product groups are selected which are a likely candidate for sequence deliveries. Two product groups are selected which are delivered from external suppliers. These two groups are the drive shafts and the headlights. The sheet metal plant is considered as an internal supplier. 3D laser components, which are produced in the sheet metal plant, are the third product group that is analysed.

9.1. Drive Shafts

Currently, drive shafts are directly delivered JIT or JIS from an external supplier to the truck plant in the Netherlands. The shafts are stored outside the truck plant. By checking the inventory data for drive shafts between week 1 and week 22 of 2021, it is found that TP has on average 196 slow moving drive shafts on stock which are delivered Just-In-Sequence. The planned yearly demand for these slow moving drive shafts is equal to 35,070. TP has 240 production days per year. *196/35,070*240=1.34* gives the coverage level for the slow moving drive shafts in days. These shafts are already delivered in sequence. Therefore, the coverage level of these components are used as a reference level for sequence components. The truck plant produces 15.5 hours per day. When assuming a tact time of 5 minutes per truck, the current coverage level of the slow moving drive shafts is equal to *1.34*15.5*60/5=249* trucks.

On the other hand, TP has on average 432 fast moving drive shafts on stock which are delivered Just-In-Time. The planned yearly demand for the fast moving drive shafts is 53,733. The coverage level is equal to *432/53,733*240=1.93* days. The current coverage level of the fast moving drive shafts is equal to *1.93*15.5*60/5=359* trucks. According to the Pearl Chain method, regular inventories can be reduced due to sequence deliveries. Important condition to make an inventory reduction possible: the production process at TP becomes more reliable and a constant flow of new materials is maintained. Drive shafts are delivered to TP one time per day. That means that the drive shafts inventory needs to cover at least 1 production day. When using a coverage of 1.34 days, just as for the slow moving drive shafts, a new Pearl Chain inventory level can be calculated. So the new stock height of the drive shafts could become equal to *432/1.93*1.34=300* drive shafts. A reduction of approximately 30.6% of the inventory, which is equal to 132 drive shafts, could be achieved when using a Pearl Chain coverage level of 1.34 production day instead of the current TP inventory levels.

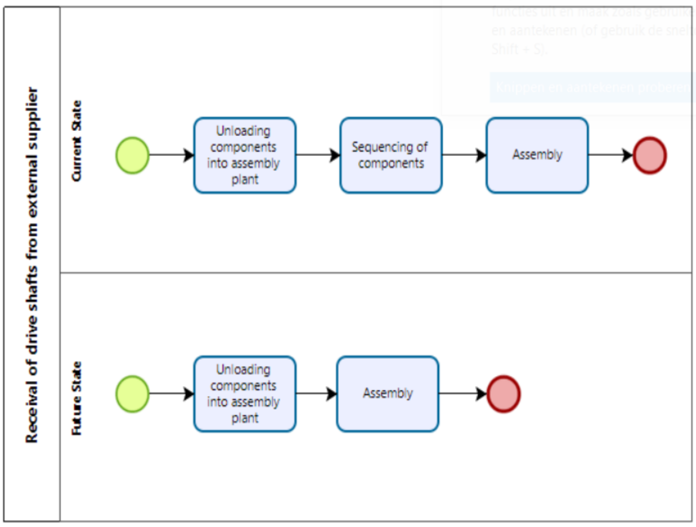


Figure 18: The current state vs future state receival process of drive shafts

Next to an inventory reduction, other savings can be gained by developing a simpler process. When all the drive shafts are delivered in sequence, the process becomes less complex (see Figure 18). Currently, a lot of fast moving drive shafts are delivered Just-In-Time. Therefore, these drive shafts are delivered in batches. After unloading the drive shafts, the components should be sequenced before they are assembled to the truck. This process step is skipped when the parts are delivered Just-In-Sequence.

9.2. Headlights

Headlights are just as the drive shafts delivered from an external supplier. However, head lights are first stored in a central warehouse. Subsequently, they are delivered JIT or JIS to the truck plant. Therefore, the delivery of headlights requires some extra processing steps. Between week 1 and week 22 of 2021, TP has on average 1,991 headlights on stock. The planned yearly demand for headlights is equal to *84,142*. *1,991/84,142*240=5.68* gives the coverage level for headlights in days. The coverage level in trucks is equal to *5.68*15.5*60/5=1,056*. The daily need for headlights is *84,142/240=351*. Headlights are also delivered once a day. When again using a Pearl Chain coverage of 1.34 production day for external suppliers, the headlights inventory can be reduced to *351*1.34=470* headlights. This is a difference of 1,521 headlights which is equal to an approximate reduction of 76.4%.

Not only the inventory of the headlights can be reduced by using the Pearl Chain model. The process also becomes less complex in that case. No intermediate storage in the warehouse is needed. When the headlights are immediately delivered to the truck plant, a lot of savings are made. In Figure 19, the current state vs the future state receival process of the headlights is displayed. Unloading of goods into the intermediate warehouse is not necessary anymore when using the Pearl Chain method. The goods do not have to be picked and sequenced and no transportation is needed from the warehouse to the truck plant. The only important activity that is left is the unloading of the trailers according to the Kanban technique. So the current receival process follows the given order for intermediate warehouse components: unloading, picking, sequencing, transportation and again unloading. In the new Pearl Chain process, the only needed activity is unloading the trailer. The new process is less complex and much cheaper. A lot of handling costs can be saved. Not only for headlights, but for most of the components that are currently stored in one of the intermediate warehouses.

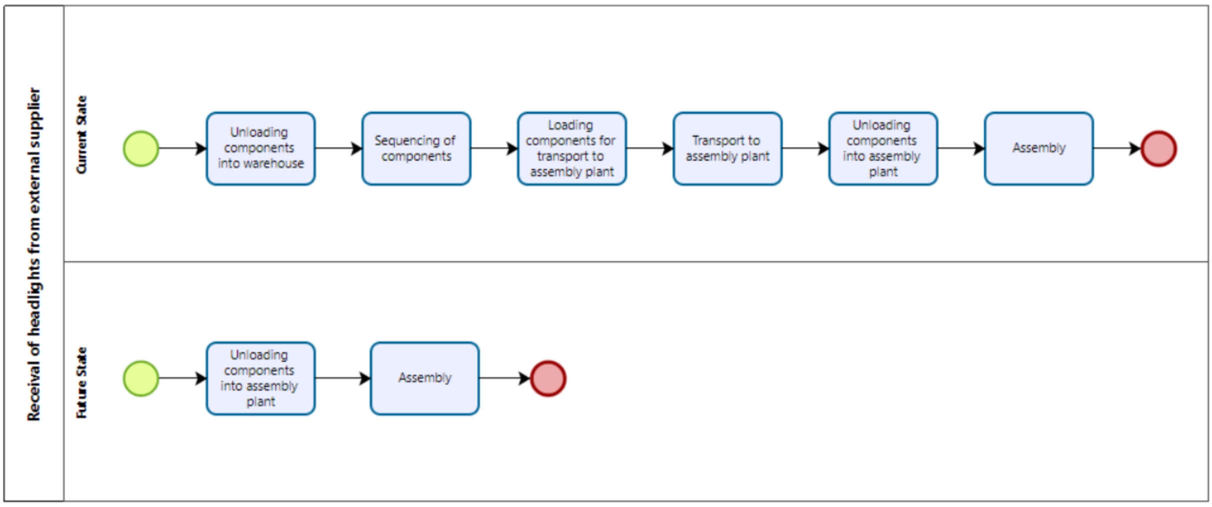


Figure 19: The current state vs future state receival process of headlights

9.3. 3D Laser Components

Several products are produced in the sheet metal plant from TP with the help of 3D laser techniques. Heat caps or battery boxes for example. Finished 3D laser components are transported to an intermediate warehouse. Subsequently, they are delivered JIT or JIS from the warehouse to the truck plant. Just as for the headlights, a lot of extra steps are required which complicate the process. The sheet metal plant is located very close to the truck plant. Even closer than the intermediate warehouse. So the 3D laser components first make a detour before they arrive in the truck plant. If the production sequence remains stable, the sheet metal plant can deliver 3D laser components according to the Supply In Line Sequence method. This method is very suitable for nearly located suppliers. The sheet metal plant already uses this method for some product specific components like colour parts. Therefore, it should be possible to use this delivery method on a wider scale. Even more product groups could be delivered SILS.

Between week 1 and week 22 of 2021, TP has on average 2,728 3D laser components on stock. The planned yearly demand for 3D laser components is equal to 54,408 pieces. Therefore, the average stock covers *2,728/54,408*240=12.03* days. The coverage level in trucks is equal to *12.03*15.5*60/5=2,238*. The daily need for 3D laser components is *54,408/240=227* pieces. Colour parts are already delivered in sequence from the Sheet Metal Plant. Therefore, the coverage level of colour parts is taken as reference point for the 3D laser components. On average TP has 12,507 colour parts on stock. The yearly demand is 767,377. So the coverage for colour parts is equal to *12,507/767,377*240=3.91* days. When using a Pearl Chain coverage of 3.91 days, the 3D laser components inventory can be reduced to *3.91*227=888*. This is a difference of 1,840 3D laser components which is equal to an approximate reduction of 67.4%.

The SILS method can also save handling costs. In Figure 20 the current state vs the future state receival process of 3D laser components is given. The most important difference is that the components are directly transported to the assembly plant with the SILS method. So no transport to the intermediate warehouse is required. Inbound and outbound handling costs of the intermediate warehouse can also be skipped. 3D laser components are not sequenced so therefore no sequencing costs can be saved on these components.

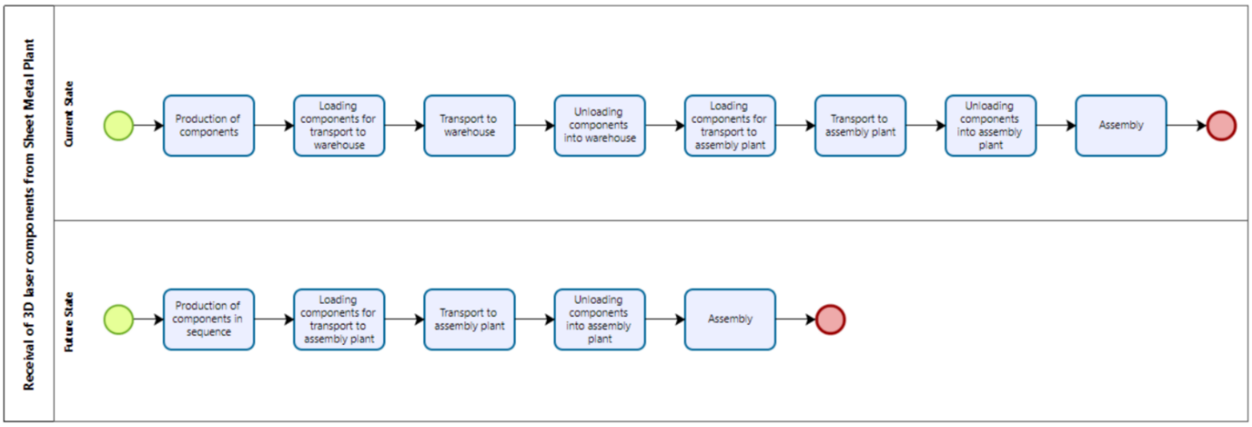


Figure 20: The current state vs future state receival process of 3D laser components

9.4. Cost savings

It is possible to calculate what the average book value is for a product group by multiplying the yearly need of a specific component with its book value. The result is then divided by the total yearly demand for the corresponding product group. Subsequently, all the component values in a product group are added up to determine the book value for an average drive shaft. The result is a book value of €273.41 per drive shaft. The book value of an average headlight is estimated at €70.49 and 3D laser components have an average book value of €36.96. From these book values, the total potential inventory reduction is calculated. The 10% rule from section 8.3.3 is again applied on the inventory reduction to calculate the possible cost savings. The book values, inventory reductions and cost savings are all given in Table 37 in euros.

Table 37: Possible cost savings of inventory reduction

PRODUCT GROUP	BOOK VALUE (€)	INVENTORY REDUCTION (€)	10% COST SAVINGS (€)
DRIVE SHAFTS	271.93	35,894.76	3,589.48
HEADLIGHTS	107.11	162,914.31	16,291.43
3D LASER COMP.	36.96	68,006.40	6,800.64

This chapter is used to determine the cost savings for three specific product groups which qualify for sequence deliveries when a stable production sequence is maintained at TP. All the three product groups are currently supplied in different ways. Drive shafts are already directly delivered to the truck plant. Headlights are delivered to the intermediate warehouse and subsequently to the truck plant. While 3D laser components are produced in the sheet metal plant, stored in the intermediate warehouse and then delivered to the truck plant. The drive shafts have the lowest cost saving since these deliveries already are delivered in sequence for a large part. Headlights and 3D laser components have a higher cost saving because their potential inventory reduction is larger. Next to this, some extra process savings can be made. When delivering these components directly to the assembly plant without intermediate storage, a lot of activities can be skipped. These activities are explained in the previous sections: 9.1, 9.2 and 9.3. In Table 38 some relevant cost parameters are given. Transport costs are not taken into account. That is because the trucks and the trains on the TP terrain transport multiple products at once. Therefore, it is very complicated to calculate cost savings on transport. When a certain product group skips the intermediate warehouse, it does not mean that the truck or train stops driving between the warehouses and the plants. It is also complicated to calculate cost savings on the sequencing of drive shafts. That is because a lot of the drive shafts are already delivered in sequence. Only fast moving drive shafts are delivered in batches. Sometimes it happens that the operator has to search a little longer for a specific drive shaft. However, most times the operator can pick the drive shaft very quickly. Therefore, it is hard to label this activity with a cost parameter.

Table 38: Handling cost parameters

ACTIVITY	COST (€)
INBOUND WAREHOUSE	2.04 per batch
OUTBOUND WAREHOUSE	2.04 per batch
SEQUENCING WAREHOUSE	0.975 per product

Because inbound and outbound costs are calculated per batch, the batch sizes are determined for headlights and 3D laser components. Headlights are mostly delivered in batch sizes of 12 to the warehouse and in batch sizes of 8 to the assembly plant. The bath sizes of the different products within the product group 3D laser components can vary. Therefore, an average batch size is calculated for the this product group. 3D laser components have an average batch size of 27 which is a weighted average based on the yearly demand per component. Subsequently the savings on handling costs are calculated for headlights and 3D laser components.

Headlights have a yearly demand of 84,142. So the approximate yearly savings on handling costs are:

*84,142/12*2.04+84,142/8*2.04+84,142*0.975=14,304.14+21,456.21+82,038.45=€117,798.80*

3D laser components have a yearly demand of 54,408. The approximate yearly savings are:

*54,408/27*2.04+54,408/27*2.04=4,110.83+4,110.83=€8,221.66*

To summarize, for all three product groups cost savings can be realised. For the warehouse components, the largest savings are possible. The results are displayed in Table 39. On all three product groups, a cost saving can be realised by reducing the inventories. Even more interesting are the yearly savings that can be made in handling costs. By developing a simpler process with less activities, a lot of money can be saved on a yearly basis.

Table 39: Possible cost savings when sequence deliveries are implemented

PRODUCT GROUP	10% RRR SAVINGS (€)	HANDLING SAVINGS (€)
DRIVE SHAFTS	3,589.48	-
HEADLIGHTS	16,291.43	117,798.80
3D LASER COMPONENTS	6,800.64	8,221.66
TOTAL	**26,681.55**	**126,020.46**

Important note to the analysis in this chapter: the used product groups in the calculations are only samples of products with different supply methods. When looking closer to all the different product groups that TP uses for a truck assembly, a lot of new product groups arise which are a likely candidate for sequence supply. One should compare the internal cost savings of sequence supply with the extra costs that a supplier asks for providing the sequence supply. With the right information provided, TP can make a sensible decision to whether sequence supply pays off for certain product groups. Potential candidates are large, cumbersome parts which are expensive to store. For example, wiring harnesses, tanks, large chassis supports and mudguards.

10. Conclusion

This chapter concludes the research. First, all the findings are summarised. Subsequently, the research questions are answered. The discussion follows where the results are interpreted, recommendations are given and limitations are presented.

10.1. Summarised Findings

The project started with the literature review. A basic theoretical understanding about the Pearl Chain concept is gained due to the literature review. Pearl Chain itself is discussed, followed by the Just-In-Sequence method and applications in the automotive industry. The gained knowledge made it possible to analyse the current situation at TP. The supportive processes are analysed, visualised and challenges are identified. The primary production process is also analysed and visualised. This analysis provides sufficient information to develop a simulation model. The current order sequence is replicated in the Plant Simulation tool. KPIs like the average buffer occupation, the average lead time and the amount of blockings are identified. The current state performance is tested and analysed. This concludes the current state analyses. The future state analyses follow after the current state analyses. Pearl Chain experts are interviewed and new insights about the Pearl Chain concept are gathered. Practical examples from the car and the truck industry are described. These examples are used to design a Pearl Chain model for TP and solutions to the current challenges are provided. The Assembly Production Control model is redesigned in order to meet the Pearl Chain requirements. For the simulation model, potential future state sequences are generated and compared with the current state sequence. The performances of the sequences are analysed and possible cost savings are calculated regarding the buffers of WIP trucks and main components. Next to this, a sample analysis is performed on some regular components. Potential cost savings are calculated for drive shafts, headlights and 3D laser components. Especially large savings can be realised for large cumbersome components which are stored and sequenced in an intermediate warehouse. Skipping the intermediate warehouse saves a lot of handling costs. Table 40 provides a brief overview of the results of all the different analyses.

Table 40: Summary of the results of all the different analyses

ANALYSIS	RESULTS
LITERATURE REVIEW	A basic theoretical understanding from the scientific literature is gained about the Pearl Chain concept, Just-In-Sequence and applications in the automotive industry.
ASSEMBLY PRODUCTION CONTROL MODEL	Analysis and visualisation of the supportive processes. Challenges regarding a Pearl Chain implementation are identified.
ASSEMBLY PROCESS	Analysis and visualisation of the primary production process. The gathered information is used to develop the simulation model.
ASSEMBLY PLANT SIMULATION CURRENT STATE	The performance of the current order sequence is investigated. Average buffer occupation is equal to 5.8 trucks and most of the blockings occur due to missing cabins, followed by missing engines.
TOWARDS A PEARL CHAIN	New Pearl Chain insights are gathered from practical examples. Solutions are provided for current challenges and the current Assembly Production Control model is redesigned.
ASSEMBLY PLANT SIMULATION FUTURE STATE	A Pearl Chain can save up to €34,000 on the trucks in the intermediate buffers and up to €305,000 on the main component buffers. Additionally, up to €210,000 per year on handling costs can be saved.
SAVINGS ON SEQUENCING	For the three analysed product groups combined, up to €27,000 can be saved by reducing the inventory. Additionally, up to €126,000 per year can be saved on handling costs. Large warehouse components are the most interesting to analyse.

10.2. Research Questions

In this section, the research questions presented in the beginning of the report are reviewed. The main question reads:

"How to design a Pearl Chain model with JIS supply for a truck manufacturer like TP?"

Sub questions were formulated in order to structurally answer the main question. The sub questions are answered in the rest of this section.

1. ***What are the opportunities and challenges specific to automotive companies when implementing Pearl Chain with JIS supply?***

A Pearl Chain production model in combination with a JIS supply system has a couple of benefits. First of all, the inventory can be decreased since goods are directly delivered to the production line and not stored in a warehouse. This saves inventory and damage costs. Next to this, unexpected overloads or shortages during the production can be prevented due to the fact that Pearl Chain production aids planning systems for the use of personnel and materials. Also a better control of the process can be maintained because the order sequence is predefined. Better planning and control lead to an improved production efficiency and a better process quality. It makes it possible for a company like TP to offer a wide variety of products to their customers. One of the challenges is that the supply chain needs a tight integration. TP has to work very closely with their suppliers. Production schedules should be shared with suppliers on predetermined periods. This requires a stable and well-functioning IT structure. The complexity of the supplier system also weighs in on these challenges. Internal challenges are process stability and organizational discipline. Process stability could be reached by investing into advanced technologies or lean methods.

2. ***How to adapt current Pearl Chain models with JIS supply for the truck industry?***

A Pearl Chain model for TP is designed after analysing the current situation. It is important to gain knowledge about the primary production process and the secondary support processes. The current processes are analysed and visualised. Challenges are identified which currently prevent the implementation of a Pearl Chain model. After that, external firms are consulted on the road towards a Pearl Chain. Flexis provides a sequencing system which is capable of sequencing a Pearl Chain. Next to this, information about the Pearl Chain model at truck producer MAN is shared. Nobleo shared their Pearl Chain experience at Nedcar and Volvo with regard to regulating the sequence stability and the material flow. SAP elaborated on how their ERP system could help TP in the future. With all the gained information in mind, a future Assembly Production Control model is designed.

3. ***How to evaluate a Peal Chain model with JIS supply?***

In the scientific literature, the Pearl Chain method is not quantitatively analysed in a production environment. Therefore, one of the goals of this report is to fill that research gap. With the help of the Plant Simulation tool, a simulation is designed to quantitatively analyse the benefits of a Pearl Chain model for TP. With the help of VRS data, the current state sequence through the assembly plan is replicated as good as possible. The relevant parameters are extracted and the model is transformed into a stochastic model. The stochastic model is validated and a method is developed to test the amount of blockings that happen before the assembly. From the current state simulation, the current buffer occupation, lead time and amount of blockings are analysed. Gradually, the sequence performance in the assembly plant and the sequence performance for the supply of main components are increased.

4. What are the possible opportunities and future challenges when implementing the Pearl Chain model with JIS supply in the truck industry?

The simulation results show clearly that increasing the sequence performance lowers the intermediate buffer occupation and the average lead time. Next to this, the amount of blockings on the deployment plan also decreases. So when the supply sequences are more stable, the delivery and supply buffers of the main components can eventually be lowered. These buffer reductions can lead to a lot of cost savings according to the Lean Six Sigma 10% rule. Up to €34,000 can be saved on the trucks in the intermediate buffers and up to €305,000 on the main component buffers. Additionally, up to €210,000 per year on handling costs can be saved at *Buffer Chassislijn*. Another advantage of a Pearl Chain is that regular components can be delivered Just-In-Time or Just-In-Sequence. The potential savings vary per product group. From the analysis conducted in chapter 9, one can conclude that the largest savings on inventory reductions and handling costs are possible for large, cumbersome components which are currently stored in a central warehouse. For example, headlights have a high potential cost saving. For future research, TP should analyse what the cost savings can be for other product groups.

The production/delivery of main components and the short frozen zone are identified as the main challenges for a Pearl Chain. A Pearl Chain model requires a frozen zone of approximately 10 days before the assembly. Currently, TP works with a semi-frozen zone in which a lot of changes occur. So a frozen zone should be implemented. Blockings on the deployment plan should be prevented by improving the FTR of the main components and a better handling of rework. In order to achieve a higher FTR, time and money should be invested in advanced technologies and lean methods for the TP production plants. A Pearl Chain enables a more accurate worker/supply planning which can also lower blockings on the deployment plan. Working/delivery schedules can also be frozen because the order sequence does not change anymore in the week before the assembly. So an additional advantage is that a more rigid planning can save costs on overtime and inventory.

5. How and to what extent will the new model be supported by SAP?

A new Pearl Chain model is certainly supported by the SAP system. SAP includes various features to ensure JIT or JIS deliveries. The newest SAP system (SAP S/4HANA) delivers 13 Fiori apps regarding material flow for an optimal user experience. SAP can also provide a new sequencing system which is currently supplied by Flexis. Possibly, an all in one deal with SAP can lower the costs for the sequencing system. Furthermore, SAP can help TP in developing a more detailed planning. The TP Mainframe plans on day level. SAP could certainly help in moving to an hour level planning. The SAP system has more functionalities than the TP Mainframe and is more user-friendly. Therefore, it is advisable to pair the road towards a Pearl Chain with the transfer towards the SAP system.

10.3. Discussion

This section discusses what the results from the research mean, how they matter and how they are limited. Next to this, recommendations are given for future research. Firstly, a method is derived to adapt current Pearl Chain models for the truck industry. The developed method includes analysing and visualising the current situation. Then, experts are consulted and the processes are redesigned. This research includes a global overview of the primary and the secondary processes. When actually implementing a Pearl Chain model, the developed method should be applied on smaller processes. So the focus should shift to the analysis and redesign of process parts. One could doubt if TP is representable for the whole truck industry. While this is a fair question, it can be refuted by the fact that the production process of a truck is very similar for all truck producers. In the truck industry, an assembly is built from a chassis, an axle set, an engine and a cabin. This is the vital difference between the car industry where an assembly is built from a chassis and an engine. A lot of literature is published about Pearl Chain in the car industry. However, the literature regarding the truck industry is very scarce. Practical examples of Pearl Chain at MAN and a simulation study regarding the truck industry are shown in this research. Therefore, the research is a good addition to the Pearl Chain literature.

The simulation is used to quantitatively analyse the benefits of the Pearl Chain model. A couple of potential cost savings are derived from the simulation. The feasibility of the different scenarios are a point for discussion. However, truck manufacturer MAN has been able to implement a Pearl Chain. Therefore, it should also be possible for TP. Next to this, the applicability of the simulation versus real life could be argued. In a simulation, there is always a certain error margin present. The variable (= the order sequence) is realistically simulated under average circumstances. The average circumstances contain a margin of error, because the circumstances like line speeds and failures are always different. On the other hand, it is impossible to simulate every aspect into detail. So therefore the simulation is developed under average circumstances. The average circumstances of course deviate from the real circumstances so a small deviation in the results will be present. However, the deviation is kept as small as possible due to the use of the average circumstances. Besides, a clear trend is visible in the results. Because of that, the results can be seen as reliable. The axle delivery buffer is not taken into account during this research. For future research, an analysis on that buffer should be conducted.

In chapter 9, a couple of cost savings are calculated for some sampled product groups. A limitation of the analysis is that the savings are only analysed for a couple of product groups. Because it is not possible to analyse all the product groups within the given timeframe, a sample is performed. The meaning of the sample analysis is to give TP sight on where the potential cost savings can be achieved. Therefore, it is important that more product groups are analysed on their potential cost savings. Large, cumbersome components with storage costs are the main candidates to be delivered in sequence. Especially a lot of savings can be realised when the intermediate storage locations are skipped and the relevant components are directly delivered to the assembly plant.

A stable Pearl Chain will take years to achieve. Time and money is needed to work smarter and more efficient. This research does not present a comprehensive road map on how the Pearl Chain model should be implemented in the truck industry. However, what this research does present is an overall analysis of the current situation and domain knowledge about the Pearl Chain method. The potential opportunities are quantitatively analysed and expressed in terms of money. On the other hand, the challenges which prevent the implementation of the Pearl Chain method are discovered and possible solutions are suggested. The goal of the research was to map the current situation at TP and to summarize where TP wants to be in a couple of years. At the same time TP wanted to know what they can gain with the help of the Pearl Chain method and what the challenges are during the implementation. This research contains the mentioned goals. So hopefully TP or other interested parties are able to use the presented information in a beneficial way.

References

Bányai, T., & Bányai, Á. (2017). Modelling of just-in-sequence supply of manufacturing processes. *MATEC Web of Conferences*, *112*, 1–6. https://doi.org/10.1051/matecconf/201711206025

Brenner, M., Langner, W., & Sautter, M. (2003). *Blueprint Supply Cockpit JIS / JIT*.

Casper, B. (2007). Volkswagen fährt mit neuem Produktionssystem effizienter. *WIREG Aktuell*, *22*.

Commisso, M. (2012). *in sequence verstrekken SKITS*.

Conze, M., Sailer, T., & Günthner, W. A. (2013). *Combined Call-Off and Transport Control for Milk Runs Based on Order Pearl Chains in the Vehicle Sector. 11*(1 OP-Annals of the Faculty of Engineering Hunedoara-International Journal of Engineering. Feb2013, Vol. 11 Issue 1, p137-142. 6p.), 137. http://search.ebscohost.com/login.aspx?direct=true&site=eds-live&db=a9h&AN=86973050

Cooper, H. M. (1988). Organizing knowledge syntheses: A taxonomy of literature reviews. *Knowledge in Society*, *1*(1), 104–126. https://doi.org/10.1007/BF03177550

Copaciu, F. V. (2013). *Analyse der Wirkzusammenhänge in der Perlenkettenmethode in der Automobilindustrie*.

Dijkman, R. M., Dumas, M., & Ouyang, C. (2008). Semantics and analysis of business process models in BPMN. *Information and Software Technology*, *50*(12), 1281–1294. https://doi.org/10.1016/j.infsof.2008.02.006

Flexis AG. (2012). Use Case MAN Truck & Bus AG: Program management, scheduling & sequencing. *VDI*, *4*.

Kahmeyer, M. (2002). Produktions-und Logistikkonzepte der Porsche AG. *VDI BERICHTE*, *1698*, 45–56.

Lorenc, A., & Szkoda, M. (2015). Customer logistic service in the automotive industry with the use of the SAP ERP system. *2015 4th IEEE International Conference on Advanced Logistics and Transport, IEEE ICALT 2015*, 18–23. https://doi.org/10.1109/ICAdLT.2015.7136584

Mayrhofer, W., März, L., & Sihn, W. (2011). Planning assistance for pearl chain forecasts and personnel assignment planning of sequenced assembly lines. *CIRP Annals - Manufacturing Technology*, *60*(1), 481–484. https://doi.org/10.1016/j.cirp.2011.03.044

Meissner, S. (2010). Controlling just-in-sequence flow-production. *Logistics Research*, *2*(1), 45–53. https://doi.org/10.1007/s12159-010-0026-5

Papoutsidakis, M., Michael, S., Sfyroera, A., & Priniotakis, G. (2021). Just-in-Sequence Technologies to Boost Automotive Supply Chain Effectiveness. *Open Journal of Applied Sciences*, *11*(01), 9–19. https://doi.org/10.4236/ojapps.2021.111a002

Raimond, B. (2016). *ASSOR - Assemblageschema*.

Randolph, J. J. (2009). A guide to writing the dissertation literature review. *Practical Assessment, Research and Evaluation*, *14*(13).

SAP. (2021). *Next Generation JIT Supply to Production: SAP S/4HANA 2020 FPS01*.

Scheffels, G. (2012). The Pearl Chain Logistics Concept. *JOT-International Surface Technology*, *5*(2), 18–21. https://doi.org/10.1365/s35724-012-0077-z

Seeman, C. (2015). Alles folgt der Perlenkette. *DVZ*.

Thissen, P. (2014). *Next step in Automotive Evolution*. 2–4.

Tomanek, D. (2018). How the Pearl Chain Concept Can Improve the Performance of Operating Theaters in Hospitals: Results of an Empirical Study. *Business Logistics in Modern Management*, *18*, 605–616.

TP. (2019). *Sequence bepaling en target setting*.

Unger, K., & Teich, T. (2009). Pearl chain design for synchronous production. In *IFAC Proceedings Volumes (IFAC-PapersOnline)* (Vol. 42, Issue 4 PART 1). IFAC. https://doi.org/10.3182/20090603-3-RU-2001.0534

Wagner, S. M., & Silveira-Camargos, V. (2011). Decision model for the application of just-in-sequence. *International Journal of Production Research*, *49*(19), 5713–5736. https://doi.org/10.1080/00207543.2010.505216

Wagner, S. M., & Silveira-Camargos, V. (2012). Managing risks in just-in-sequence supply networks: Exploratory evidence from automakers. *IEEE Transactions on Engineering Management*, *59*(1), 52–64. https://doi.org/10.1109/TEM.2010.2087762

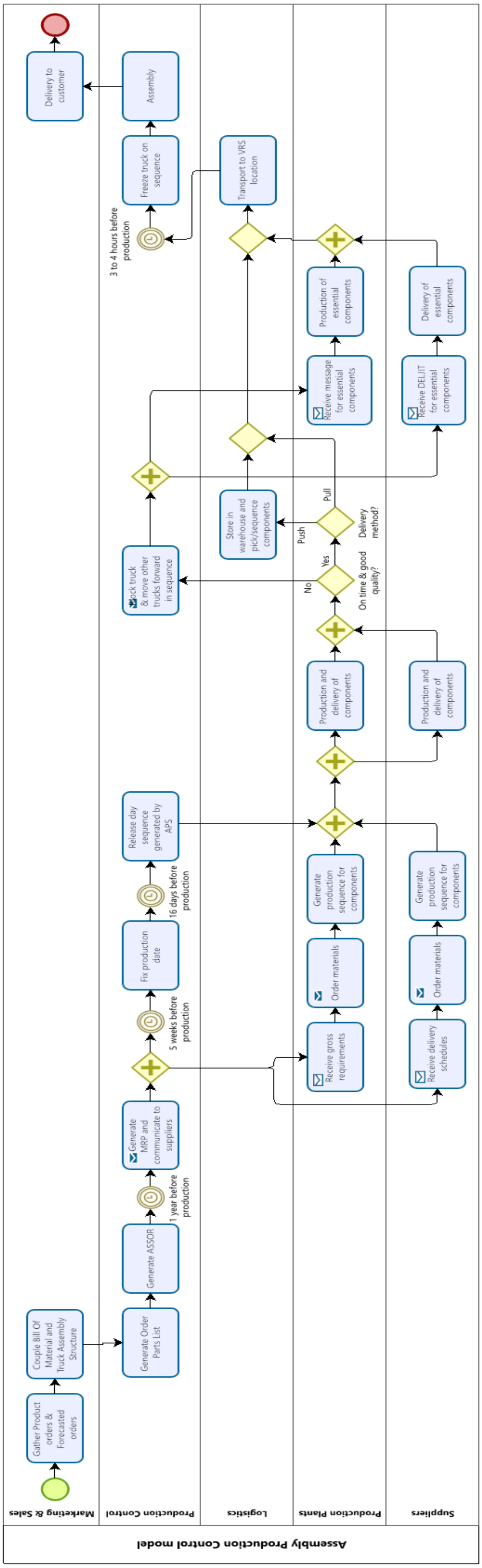
Weyer, M. (2002). Das Produktionssteuerungskonzept Perlenkette und dessen Kennzahlensystem. *Karlsruhe: Helmesverlag*, *1*.

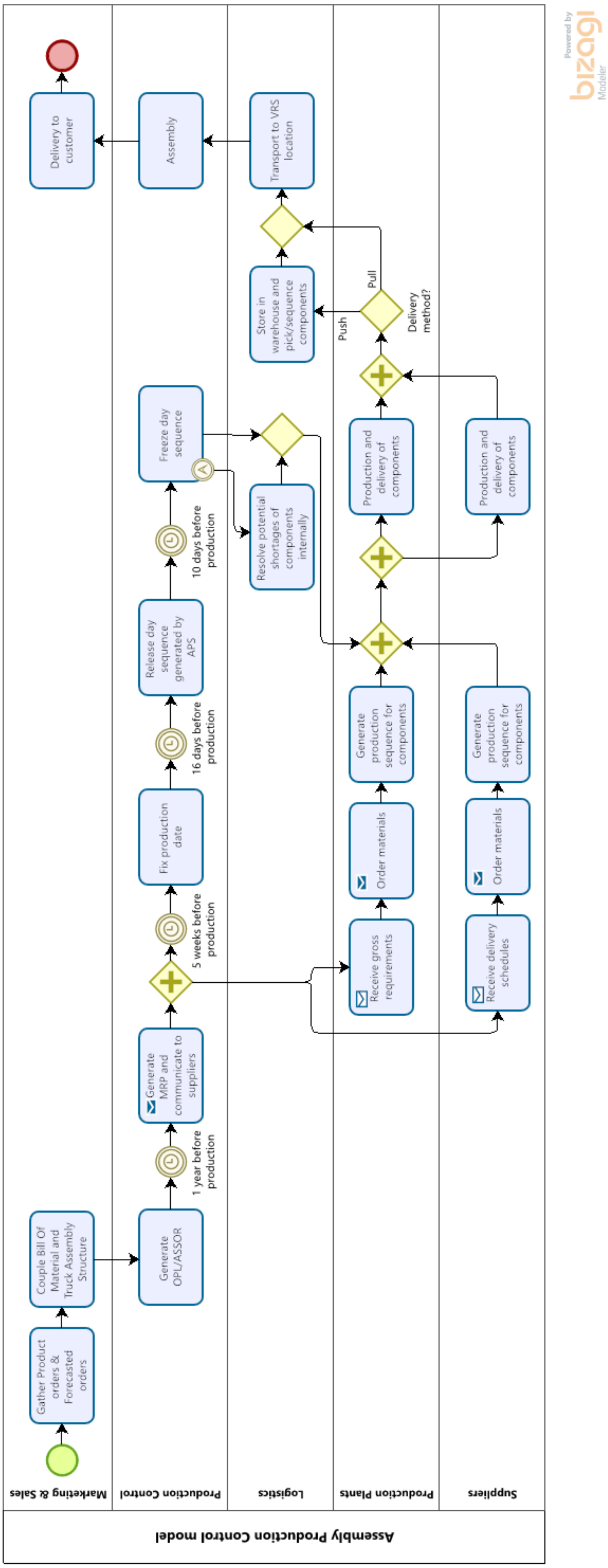
Wiering, P., Kouijzer, M., & Noteborn, L. (2017). *Logistiek voor dummies Truckfabriek*.

Wieringa, R. J. (2014). Design science methodology: For information systems and software engineering. In *Design Science Methodology: For Information Systems and Software Engineering*. https://doi.org/10.1007/978-3-662-43839-8

Appendix

1. Assembly Production Control model – Current State
2. Assembly Production Control model – Future State
3. Research Proposal
4. Literature Review


Assembly Production Control model
Marketing & Sales
Production Control
Logistics
Production Plants
Suppliers
Gather Product orders & Forecasted orders
Couple Bill Of Material and Truck Assembly Structure
Generate Order Parts List
Generate ASSOR
1 year before production
Generate MRP and communicate to suppliers
5 weeks before production
Fix production date
16 days before production
Release day sequence generated by APS
Receive gross requirements
Order materials
Generate production sequence for components
Receive delivery schedules
Production and delivery of components
On time & good quality?
No
Yes
Delivery method?
Push
Pull
Store in warehouse and pick/sequence components
Pick truck & move other trucks forward in sequence
Receive message for essential components
Production of essential components
Receive DELJIT for essential components
Delivery of essential components
Transport to VRS location
3 to 4 hours before production
Freeze truck on sequence
Assembly
Delivery to customer


Assembly Production Control model
Marketing & Sales
Production Control
Logistics
Production Plants
Suppliers
Gather Product orders & Forecasted orders
Couple Bill Of Material and Truck Assembly Structure
Generate OPL/ASSOR
1 year before production
Generate MRP and communicate to suppliers
5 weeks before production
Fix production date
16 days before production
Release day sequence generated by APS
10 days before production
Freeze day sequence
Resolve potential shortages of components internally
Receive gross requirements
Order materials
Generate production sequence for components
Production and delivery of components
Receive delivery schedules
Order materials
Generate production sequence for components
Production and delivery of components
Delivery method?
Push
Pull
Store in warehouse and pick/sequence components
Transport to VRS location
Assembly
Delivery to customer

Research Proposal – Truck Producer: “Towards a Pearl Chain”

L. Vliegen – 1395807

24-2-2021

Supervisors:

dr. B. Aysolmaz	–	TU Eindhoven, IS
dr. ir. R. Dijkman	–	TU Eindhoven, IS
ir. A. van den Broeke	–	Truck Producer, Q&CI
ir. A. Tummers	–	Truck Producer, IT

Content

1. Introduction

Nowadays the struggle to move to a different logistics model is immense, especially for a billion dollar company like TP. Processes become so big that they are hard to handle, let alone redesign. However to keep moving forward as a company, one needs to continuously improve their processes. This research is conducted at the Quality & Continuous Improvement department of TP. Specifically, the goal is to gather recommendations for redesigning the Assembly Production Control process. More information about the subject is provided in section 2. Hereafter, the scientific relevance is explained in section 3. In section 4 the research questions are given and section 5 presents the methodology. Finally, in section 6 the planning of the project is drafted.

2. Background

In the following section the background for this research is explained. A company description is given, followed by the scope and the problem statement.

2.1. Company description

TP is a Dutch truck manufacturing company and a subsidiary of an American company. The American company is a global quality leader in the design and manufacturing of high-end light, medium and heavy commercial vehicles. The American company also designs and manufactures advanced diesel engines, provides financial services and information technology, and distributes truck parts related to its main business. The TP headquarters and its main factory are in the Netherlands. Its core activity is the development, production, marketing, sales and service of trucks for other organizations (Business2Business). Each truck is customized, based on the 'build to order' principle. The cabs and axles are produced at their plants in Belgium. Some truck models sold under the TP brand are designed and manufactured by TP's assembly plant in England. At the moment, TP produces three series of trucks. The first series are specialized for city traffic, the second series are for regional, national or international transport and the third series are specialized in longer distances.

2.2. Scope

The project is conducted at the Quality & Continuous Improvement department of TP. In Figure 2 a global organization chart of the departments within TP is given.

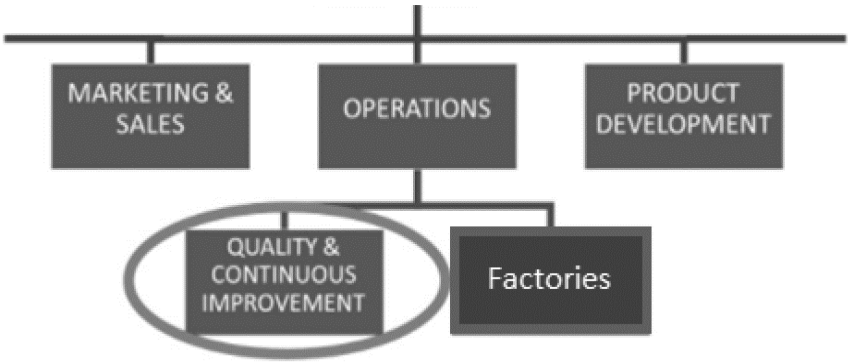


Figure 2: Global organogram of TP

The Quality & Continuous Improvement (Q&CI) department is active in a couple of areas. Therefore the department exists out of a variety of people. The department has logistics engineers, production engineers, quality engineers, data scientists and master black belts on their payroll. Therefore the department brings together a wide variety of expertise in different fields. The project is mainly related to the logistics part of the Q&CI department. TP wants to move towards a Pearl Chain model. In this concept, the production sequence of orders is determined beforehand and should be set in stone. As a consequence, materials can be delivered by suppliers via the Just-In-Sequence (JIS) method. This will improve planning reliability for suppliers as well as possibilities for optimization of (safety) stock. However, due to the high customization (i.e. a complex Bill-Of-Materials) and a complex supply chain network, the road towards the Pearl Chain model is challenging for an automotive company like TP. More specifically, the current Assembly Production Control model at TP is currently set up too high-level (i.e. on a daily level) and it is not transparent enough to be able to implement a Pearl Chain model. Therefore this research needs to be conducted, before any further implementations can be made.

2.3. Problem statement

The reason why TP wants to move towards the Pearl Chain in combination with JIS supply is because other automotive companies have already walked that road successfully. The benefits of the Pearl Chain model are described in the scientific literature. Since 1997 the production of the Mercedes-Benz A-Class in Rastatt is planned according to the Pearl Chain Concept (Weyer, 2002). The Porsche plant in Zuffenhausen also defines a target sequence at the beginning of the construction of a carcass. According to their own declaration this target sequence is maintained for 99% (Kahmeyer, 2002). This shows how good Porsche is in controlling their material flow. Porsche also has built a fully automatic paint shop which is based entirely on the Pearl Chain concept (Scheffels, 2012).

The story of Volkswagen has its origin in a collaboration between the University of Applied Sciences and Volkswagen Sachsen in Zwickau, Germany. This plant became a pilot for implementing the Pearl Chain Manufacturing Organization in 2007. It was one of their first attempts to introduce the new integrated Volkswagen production system (Casper, 2007). Now, the Pearl Chain concept is an element of the "new logistics concept". The Audi production in Neckarsulm serves as a reference plant for implementation of the Pearl Chain Concept across the Volkswagen-Group (Seeman, 2015).

The application of the Pearl Chain method in the automotive industry shows that a stable order sequence can optimize production. An early order planning targets a high capacity utilization and ensures a continuous production flow. A 'calmed' production process responds positively to everyone involved in the process of value creation (Copaciu, 2013). The given examples are all of manufacturers of passenger cars, because no examples could be found for truck manufacturers in the scientific literature. For truck production, they use a body on a frame. These frames are heavier, more rigid and durable than the frames of cars and they allow them to transport heavier loads without deforming. These frames are used for pickups and large SUVs. Cars commonly use a unibody design. In this case, the body of the car itself is the frame. This is the difference between truck production and car production and it can therefore be stated as a research gap for this project. After all, the production between trucks and cars does not differ very much which makes it interesting to investigate this topic. Car and truck manufacturers both use the same assembly process where all parts are produced separately and assembled at the end.

The problem for TP is the fact that it is not easy to move towards a Pearl Chain. Enough examples can be found of other automotive producers who implemented Pearl Chain successfully. However, every case is different. TP needs a customized plan on how to proceed. At TP they already use sequencing and a lot of the materials are already delivered according to the Just-In-Sequence method. However, the lead times of the current production model are not flexible enough and the time units are too roughly estimated (i.e. days instead of minutes).

Before further implementations can be made the current Assembly Production Control model should be analysed and evaluated. The current challenges which prevent TP to move to the Pearl Chain model should be mapped. Hereafter, the process needs to be redesigned so that in the future the Pearl Chain can be implemented as efficiently as possible. Additionally, TP wants to move from their original ERP system DPICS (TP Production & Inventory Control System) to SAP. Therefore the new Pearl Chain model should fit the SAP program.

The main goal of this project is to design a Pearl Chain model for an automotive company like TP, based on the latest insights in literature and best practices. TP will use this model as input for a possible future system implementation.

3. Scientific Relevance

Section 3 is used to elaborate on the scientific relevance of the research. The concepts Pearl Chain and Just-In-Sequence are shortly discussed followed by some application of these concepts.

3.1. Pearl Chain

The term 'Pearl Chain' is frequently used in the scientific literature. For example, the Pearl Chain for synchronous production is described by Unger & Teich (2009). The paper elaborates how Pearl Chain can be used for successfully introducing lean production or management systems. TP also uses synchronous production since all the different parts of a truck are made in different factories. Other literature expresses how planning assistance for Pearl Chain forecasts and personnel assignment at assembly lines can be handled (Mayrhofer et al., 2011), which also could be a big issue for TP. Also the use of Pearl Chain outside the automotive sector is described (Tomanek, 2018). A study is performed about how the Pearl Chain concept can improve the performance of operating theatres in hospitals based on literature about Pearl Chain in the automotive industry. The adaptation of the Pearl Chain concept is based on the idea of a stable sequence of patients in the operating room on the day of surgery. It aims to improve patient satisfaction through reliable plans. Based on empirical results, it is impractical to transfer the Pearl Chain concept to the operating room of the hospital as a whole. However, it can be helpful to give specific recommendations for the hospital taking into account factors such as the department and emergency rate. It shows that the concept Pearl Chain is most applicable to the manufacturing/automotive industry.

3.2. Just-In-Sequence

The term 'Just-In-Sequence' is a more popular term than 'Pearl Chain' in the scientific literature. A lot of literature is already written about JIS. For example how to control JIS flow-production (Meissner, 2010) or how to model JIS supply of manufacturing processes (Bányai & Bányai, 2017). Risks in JIS supply chains are presented and methods to manage these risks are elaborated (Wagner & Silveira-Camargos, 2012). Hereby exploratory evidence is used from the automotive industry. In other literature new JIS technologies are presented which should boost the supply chain effectiveness of the automotive industry (Papoutsidakis et al., 2021). Even literature is found about JIS supply based on the SAP ERP system. Since TP plans to migrate from their current self-made ERP system to SAP, this article could be very helpful.

3.3. Current Application of Pearl Chain and JIS in Automotive Sector

Nedcar in Born already successfully implemented the Pearl Chain. For Nedcar a study is performed to design a Supply Cockpit to ensure JIS/JIT supply (Brenner et al., 2003). The planned Pearl Chain includes 7-day orders, with approximately 1,200 orders per day. The next day is planned in the early afternoon and then added to the end of the existing Pearl Chain. The Pearl Chain is also the basis for the planned inbound supply, and the supply must cover the demand generated by each pearl in the chain. There are a total of about 700 related JIS and JIT parts (60 pieces per pearl) and about 15,000 warehouse parts (1000-1200 pieces per pearl). The study describes the main system functions that are required to plan and execute the business process of Nedcar's production supply. The actual configuration of the fully loaded trucks is calculated based on the actual Pearl Chain and the actual coverage of the parts required. The study at Nedcar can be used as framework when implementing a Pearl Chain model at TP.

A way to handle the logistic processes for a Pearl Chain in the automotive sector, is to use milk runs (Conze et al., 2013). A milk run is a delivery method used to transport mixed loads from different suppliers to one customer. Milk runs in combination with a Pearl Chain and JIS supply can ensure fully loaded trucks. Compared with other transport modes, milk runs requires more planning and coordination. However, case studies show that the potential can be increased under the right conditions. For the German freight area up to 60% of transportation costs can be saved. Additionally, inventory costs will also lower, since the JIS concept is used. When combined, the two presented applications can be very beneficial for this project. What stands out in most of the literature is that Pearl Chain model applications are not evaluated well in a quantitative manner. This can be indicated as a research gap.

By elaborating on the previously mentioned literature and contributing to TP's specific wishes a balance is maintained between the rigor of this research and it's scientific relevance. A lot of scientific literature can be found about the terms 'Pearl Chain' and 'Just-In-Sequence' and this literature will be used to improve the scientific relevance of the research. Next to this, the wishes of TP are carefully considered to ensure that the project also is rigorous.

4. Research questions

The research questions are given in this section. First the main question is given. Hereafter, a framework is presented to formulate the sub questions.

4.1. Main Research Question

The main goal of this research is to design a Pearl Chain model for an automotive company like TP. In that way suppliers can deliver the materials via the Just-In-Sequence method. The model will be used as input for a possible future system implementation. Therefore the main research question reads:

'How to design a Pearl Chain model with JIS supply for an automotive company like TP?

To find this optimal Pearl Chain model, a couple of steps need to be taken. These will be further defined by the sub-questions in the section 3.2.

4.2. Sub Questions

The Design Science methodology of Wieringa (2014) is used to divide the project in four phases. The Design Cycle framework is given in Figure 3. The project starts with the problem investigation. Hereafter the treatment design and the treatment validation phase follow. In these phases a new Pearl Chain model for TP is designed and evaluated. The project ends in the treatment implementation phase. The cycle is done once, so the implementation evaluation is no part of this research. The Design Science Methodology is used to design a Pearl Chain model in combination with JIS supply for TP. In this case, the new Pearl Chain model can be called the artifact that will treat the stated problem.

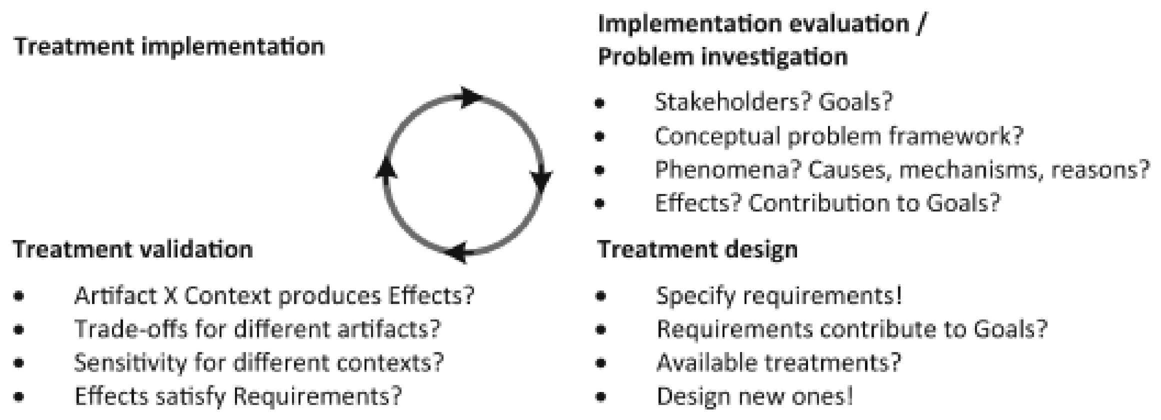


Figure 3: Design Cycle

The first phase is used to get a better understanding of the problem. Current insights about Pearl Chain and JIS are analysed, because they are needed to treat the problem. Next to this, also the current state of the Assembly Production Control process is reviewed. The first research question will be answered in this phase.

6. *What are the opportunities and challenges specific to automotive companies when implementing Pearl Chain with JIS supply?*

Analysing the current state of the Assembly Production Control process in the first phase, makes it possible to answer the second question in the treatment design phase. This phase is used to design a possible solution for the problem. The design, also known as the artifact, is a new Pearl Chain model for TP.

7. *How to adapt current Pearl Chain models with JIS supply for the truck industry?*

In the treatment validation phase the designed solution is evaluated. In that way, question 3 can be answered. The second and the third phase can be partially intertwined. While evaluating a solution, one will get new insights. These insights make it possible to adapt the design. The new design will then be evaluated again. For evaluating the new Pearl Chain model, another artifact will be designed. This artifact is presented in section 5.

8. *How to evaluate a Peal Chain model with JIS supply?*

The implementation phase is not fully executed in this project. However, recommendations are given on how to implement the developed treatments. In the implementation phase question 4 and 5 are answered. TP needs recommendations about the consequences of implementing a new Pearl Chain model. They want to know what the possible opportunities will be (i.e. lower lead time or costs) and how the difficulties will look like during the implementation of the model. Additionally, since TP wants to move to SAP, the fifth research question is drafted. It is important that the new model fits the SAP program to ensure full functionality. SAP is an ERP system that is widely used over the entire world, so therefore it is also interesting to investigate this topic from a scientific perspective.

9. *What are the possible opportunities and future challenges when implementing the Pearl Chain model with JIS supply in the truck industry?*
10. *How and to what extent will the new model be supported by SAP?*

Section 5 is used to elaborate on the research methods per phase.

5. Methodology

In section 5 the research methods of the project are elaborated per phase. First the problem investigation, followed by the treatment design, treatment evaluation and the treatment implementation. At the end the deliverables are presented per phase.

5.1. Problem investigation

6. *What are the opportunities and challenges specific to automotive companies when implementing Pearl Chain with JIS supply?*

For this project, literature about the concepts 'Pearl Chain' and 'Just-In-Sequence' needs to be gathered and assessed. The artifact used is the methodology presented by Randolph (2009). He describes the stages of conducting a literature review. The taxonomy of the literature review can be classified according to six characteristics: focus, goal, perspective, coverage, organisation and audience (Cooper, 1988). The taxonomy of the literature review is given in Table 1.

Table 41: Taxonomy of the literature review

What	**How**
Focus	Research methods/outcomes and applications with regard to Pearl Chain and/or Just-In-Sequence method
Goal	Integrate all the gathered information
Perspective	Neutral point of view
Coverage	All open source scientific articles in English, Dutch or German
Organisation	Conceptual format based on Pearl Chain and Just-In-Sequence method
Audience	Practitioners in the field and scholars who are specialised on the given subjects

Randolph describes the stages of conducting a literature review. These stages will be followed during the literature review. They are formulated as follows:

6. Problem formulation
7. Data collection
8. Data evaluation
9. Analysis and interpretation
10. Public presentation

7. *How to adapt current Pearl Chain models with JIS supply for the truck industry?*

Information should be gathered about the Assembly Production Control model. To gather information about a process, one should follow that process from start to finish. That means documenting every step of the specific process and interviewing the stakeholders. The choice for a structured or unstructured interview format still has to be made. This question is used to get a better understanding of the production control processes at TP. After all the needed information is gathered, the question can be answered. First the current state has to be visualized. Hereafter, the current state is evaluated based on relevant KPIs. The methods which are used to answer these questions are specified in sections 5.2. and 5.3.

5.2. Treatment design

The previous phase should give some insights. After the problem investigation phase, Q2 can be answered. It should be clear what the requirements are for TP to implement a Pearl Chain model with JIS supply. These insights will be used to design a future state Pearl Chain model for TP.

To answer Q2 a couple of artifacts are used. For designing the process models, the Business Process Model and Notation is used. Business Process Model and Notation (BPMN) is a standard notation used to capture business processes, especially at the domain analysis and advanced system design levels. More on BPMN can be found in "Semantics and analysis of business process models in BPMN" (Dijkman et al., 2008).

The tool used for drawing the process charts is Bizagi Modeler. Bizagi provides a business process management (BPM) suite whose key functions include the modelling, automation and execution of business processes. The software's process modelling tools enable managers to use drag and drop capabilities to build visual business processes. That is why Bizagi is used for these activities.

5.3. Treatment validation

8. *How to evaluate a Peal Chain model with JIS supply?*

A simulation is developed of the future state to detect future challenges and possible opportunities of a Pearl Chain model with JIS supply. The same method is used in the first phase to investigate the current challenges in the Assembly Production Control model (Q2). From the analyses in the previous phases, a couple of KPIs can be determined. These KPIs will be analysed in the simulation. When both simulations are finished, it is possible to compare the current state with the future state in a simulation study based on the important KPIs. The simulation study will fill a research gap in the scientific literature, since Pearl Chain model applications are not evaluated very well in a quantitative manner.

The simulations are likely to be made in the programming language Python. It is a dynamic open source programming language which is nowadays used as standard language at the TU Eindhoven. Students at the TU Eindhoven learn their basic programming skills in Python so therefore the choice is made to use this language. SimPy is a process-based discrete event simulation framework based on standard Python. The process in SimPy is defined by the Python generator function. For example, it can be used to model active components such as customers, vehicles, agents or products. SimPy also provides various types of shared resources to model congestion points with limited capacity (such as servers or checkout counters). The simulation can be performed as fast as possible, in real time or by manually stepping through events. For a detailed instruction about SimPy, see "Introduction to Discrete-Event Simulation and the SimPy Language" (Cassandras & Lafortune, 1999). Another option is to use TP's own simulation tool which is called Plant Simulation. At the moment the preference is to use Simpy, however the final choice for the simulation tool still has to be made.

5.4. Treatment implementation

> *9. What are the possible opportunities and future challenges when implementing the Pearl Chain model with JIS supply in the truck industry?*
> *10. How and to what extent will the new model be supported by SAP?*

The final phase is used to give recommendations to TP. No implementation will take place, only advice is given about future implementations. The interviews with the domain experts in the problem investigation phase should give a lot of insights which are important to keep in mind during a future implementation. Next to this, the validation phase should identify a couple of bottlenecks for the current state and the future state. In the implementation phase these bottlenecks are analysed and solutions for these bottlenecks should be brought forward. The possible opportunities of implementing a Pearl Chain model with JIS supply at TP are also analysed. In other words, will the implementation of a Pearl Chain model at TP lead to for example a lower lead time and lower costs. Additionally, a check will be performed to find to what extent the new model will be supported by SAP, since TP wants to transfer their business to this ERP system. Lastly, the final conclusions and recommendations are drafted and the project is finalized.

5.5. Deliverables

In Table 2 the deliverables per phase are presented.

Table 42: Deliverables per Design Phase

Design Phase	**Deliverables**
Problem investigation	• Literature review of the concepts 'Pearl Chain' and 'JIS' • Interviews about the Assembly Production Control model • Visualization of the current Assembly Production Control model • Simulation of the current Assembly Production Control model
Treatment design	• List of requirements for a Pearl Chain model with JIS supply • Visualization of the future Pearl Chain model with JIS supply
Treatment validation	• Simulation of the future Pearl Chain model with JIS supply • Simulation study of the current state vs the future state
Treatment implementation	• Final conclusions and recommendations

6. Project Plan

The project plan is presented in this section. In Figure 4 a Gantt chart is displayed of the project plan. Table 3 on the following page gives a more detailed week planning. Also a short elaboration on how the quality of the project will be maintained is given in this section.

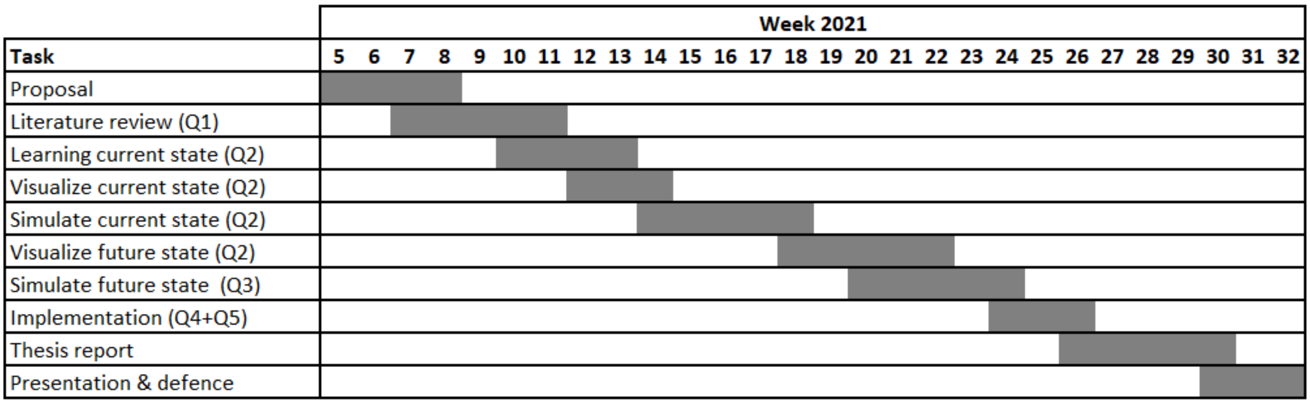


Figure 4: Gantt chart of the project plan

The quality of this project is maintained by planning a progress meeting with the company supervisor every two weeks. Next to this, a monthly update takes place which includes three graduation students at the Quality & Continuous Improvement department and their supervisors. Every student gets 30 minutes to present his/her progress. This will motivate the students, because it holds an interaction aspect, which is good to have during the COVID-19 pandemic. Also a monthly meeting with the school supervisor is planned to make sure that school is notified of the progress.

Table 43: Week planning

Week	Tasks
2021-5 (1/2)	Research proposal
2021-6 (8/2)	Research proposal
2021-7 (15/2)	Research proposal Literature review
2021-8 (22/2)	Finish research proposal Literature review
2021-9 (1/3)	Literature review
2021-10 (8/3)	Literature review Interviewing stakeholders of Assembly Production Control model
2021-11 (15/3)	Finish literature review Interviewing stakeholders of Assembly Production Control model
2021-12 (22/3)	Interviewing stakeholders of Assembly Production Control model Visualize Assembly Production Control model
2021-13 (29/3)	Interviewing stakeholders of Assembly Production Control model Visualize Assembly Production Control model
2021-14 (5/4)	Finish visualization of Assembly Production Control model Create simulation of Assembly Production Control model
2021-15 (12/4)	Create simulation of Assembly Production Control model Evaluate Assembly Production Control model
2021-16 (19/4)	Create simulation of Assembly Production Control model Evaluate Assembly Production Control model
2021-17 (26/4)	Create simulation of Assembly Production Control model Evaluate Assembly Production Control model
2021-18 (3/5)	Finish simulation of Assembly Production Control model Design Pearl Chain model
2021-19 (10/5)	Design Pearl Chain model
2021-20 (17/5)	Design Pearl Chain model Create simulation of Pearl Chain model
2021-21 (24/5)	Design Pearl Chain model Create simulation of Pearl Chain model Evaluate Pearl Chain model
2021-22 (31/5)	Finish design of Pearl Chain model Create simulation of Pearl Chain model Evaluate Pearl Chain model
2021-23 (7/6)	Create simulation of Pearl Chain model Evaluate Pearl Chain model
2021-24 (14/6)	Finish simulation of Pearl Chain model Draw conclusions and give recommendations
2021-25 (21/6)	Draw conclusions and give recommendations
2021-26 (28/6)	Draw conclusions and give recommendations Work on thesis report
2021-27 (5/7)	Work on thesis report
2021-28 (12/7)	Work on thesis report
2021-29 (19/7)	Work on thesis report
2021-30 (26/7)	Finish thesis report Prepare for presentation
2021-31 (2/8)	Prepare for presentation
2021-32 (9/8)	Final presentation and defence

References

Bányai, T., & Bányai, Á. (2017). Modelling of just-in-sequence supply of manufacturing processes. *MATEC Web of Conferences*, *112*, 1–6. https://doi.org/10.1051/matecconf/201711206025

Brenner, M., Langner, W., & Sautter, M. (2003). *Blueprint Supply Cockpit JIS / JIT*.

Casper, B. (2007). Volkswagen fährt mit neuem Produktionssystem effizienter. *WIREG Aktuell*, *22*.

Cassandras, C. G., & Lafortune, S. (1999). *Introduction to Discrete-Event Simulation*. 591–661. https://doi.org/10.1007/978-1-4757-4070-7_10

Conze, M., Sailer, T., & Günthner, W. A. (2013). *Combined Call-Off and Transport Control for Milk Runs Based on Order Pearl Chains in the Vehicle Sector. 11*(1 OP-Annals of the Faculty of Engineering Hunedoara-International Journal of Engineering. Feb2013, Vol. 11 Issue 1, p137-142. 6p.), 137. http://search.ebscohost.com/login.aspx?direct=true&site=eds-live&db=a9h&AN=86973050

Cooper, H. M. (1988). Organizing knowledge syntheses: A taxonomy of literature reviews. *Knowledge in Society*, *1*(1), 104–126. https://doi.org/10.1007/BF03177550

Copaciu, F. V. (2013). *Analyse der Wirkzusammenhänge in der Perlenkettenmethode in der Automobilindustrie*.

Dijkman, R. M., Dumas, M., & Ouyang, C. (2008). Semantics and analysis of business process models in BPMN. *Information and Software Technology*, *50*(12), 1281–1294. https://doi.org/10.1016/j.infsof.2008.02.006

Kahmeyer, M. (2002). Produktions-und Logistikkonzepte der Porsche AG. *VDI BERICHTE*, *1698*, 45–56.

Mayrhofer, W., März, L., & Sihn, W. (2011). Planning assistance for pearl chain forecasts and personnel assignment planning of sequenced assembly lines. *CIRP Annals - Manufacturing Technology*, *60*(1), 481–484. https://doi.org/10.1016/j.cirp.2011.03.044

Meissner, S. (2010). Controlling just-in-sequence flow-production. *Logistics Research*, *2*(1), 45–53. https://doi.org/10.1007/s12159-010-0026-5

Papoutsidakis, M., Michael, S., Sfyroera, A., & Priniotakis, G. (2021). Just-in-Sequence Technologies to Boost Automotive Supply Chain Effectiveness. *Open Journal of Applied Sciences*, *11*(01), 9–19. https://doi.org/10.4236/ojapps.2021.111a002

Randolph, J. J. (2009). A guide to writing the dissertation literature review. *Practical Assessment, Research and Evaluation*, *14*(13).

Scheffels, G. (2012). The Pearl Chain Logistics Concept. *JOT-International Surface Technology*, *5*(2), 18–21. https://doi.org/10.1365/s35724-012-0077-z

Seeman, C. (2015). Alles folgt der Perlenkette. *DVZ*.

Tomanek, D. (2018). How the Pearl Chain Concept Can Improve the Performance of Operating Theaters in Hospitals: Results of an Empirical Study. *Business Logistics in Modern Management*, *18*, 605–616.

Unger, K., & Teich, T. (2009). Pearl chain design for synchronous production. In *IFAC Proceedings Volumes (IFAC-PapersOnline)* (Vol. 42, Issue 4 PART 1). IFAC. https://doi.org/10.3182/20090603-3-RU-2001.0534

Wagner, S. M., & Silveira-Camargos, V. (2012). Managing risks in just-in-sequence supply networks: Exploratory evidence from automakers. *IEEE Transactions on Engineering Management*, *59*(1), 52–64. https://doi.org/10.1109/TEM.2010.2087762

Weyer, M. (2002). Das Produktionssteuerungskonzept Perlenkette und dessen Kennzahlensystem. *Karlsruhe: Helmesverlag*, *1*.

Wieringa, R. J. (2014). Design science methodology: For information systems and software engineering. In *Design Science Methodology: For Information Systems and Software Engineering*. https://doi.org/10.1007/978-3-662-43839-8

Literature review - Truck Producer: “Towards a Pearl Chain”

L. Vliegen – 1395807

2-4-2021

Supervisors:

dr. B. Aysolmaz	–	TU Eindhoven, IS
dr. ir. R. Dijkman	–	TU Eindhoven, IS
ir. A. van den Broeke	–	Truck Producer, Q&CI
ir. A. Tummers	–	Truck Producer, IT

Content

1. Introduction

The purpose of this literature review is to gain a foundation of knowledge for my upcoming Master Thesis at TP. TP is a Dutch company and subsidiary of an American company. Its core activity is the development, production, marketing, sales and service of trucks for other organizations (Business2Business). Each truck is customized based on the "build-to-order" principle. At TP, they want to move towards a Pearl Chain model. In this concept, the production sequence of orders is determined beforehand and should be set in stone. As a consequence, materials can be delivered by suppliers via the Just-In-Sequence (JIS) method. This will improve the planning reliability for suppliers as well as possibilities for optimization of (safety) stock. However, due to the high customization (i.e. a complex Bill-Of-Materials) and a complex supply chain network, the road towards the Pearl Chain model is challenging for a company like TP.

More specifically, the current Assembly Production Control model at TP is currently set up too high-level (i.e. on a daily level) and not transparent enough to be able to implement a Pearl Chain model. The main goal of the project is to design a Pearl Chain model for an automotive company like TP, based on the latest insights in literature and best practices. TP will use this model as input for a possible future system implementation.

For this project, literature about the concepts "Pearl Chain" and "Just-In-Sequence" needs to be gathered and assessed. That is done according to the guidelines (Randolph, 2009). The taxonomy of the literature review can be classified according to six characteristics: focus, goal, perspective, coverage, organisation and audience (Cooper, 1988). The taxonomy of the literature review is given in Table 1.

Table 44: Taxonomy of the literature review

What	**How**
Focus	Research methods/outcomes and applications with regard to Pearl Chain and/or Just-In-Sequence method
Goal	Integrate all the gathered information to guide the next steps of the project and identify the gaps
Perspective	Neutral point of view
Coverage	All open source scientific articles in English
Organisation	Conceptual format based on Pearl Chain and Just-In-Sequence method
Audience	Practitioners in the field and scholars who are specialised on the given subjects

The stages of conducting a literature review are described by Randolph (2009). These are:

11. Problem formulation
12. Data collection
13. Data evaluation
14. Analysis and interpretation
15. Public presentation

The first stage is the problem formulation. The question is which articles to include and which articles to exclude. Therefore the problem needs to be defined clearly and research questions should be drafted. The main research question for the literature review to answer is:

“What are the opportunities and challenges specific to automotive companies when implementing Pearl Chain with JIS deliveries?”

The following sub questions can be formulated based on the main research question:

1. How are Pearl Chain models designed for the automotive industry and other related industries?
2. How are supply systems based on the Just-In-Sequence method designed for the automotive industry and other related industries?
3. What are the benefits of the Pearl Chain model and the Just-In-Sequence method?
4. What are the challenges of the Pearl Chain model and the Just-In-Sequence method?
5. How can practical examples from the automotive industry help TP when implementing a Pearl Chain model in combination with JIS supply?

With the research questions drafted, the data collection can start. For the data collection, the use of a search engine is required. Search engines like Google Scholar, IEEE Xplore, Science Direct, Springer and ResearchGate are used. Search terms like “Pearl Chain”, “Just-In-Sequence” or “JIS” are used to gather meaningful articles. These search terms are combined with terms like “Production” or ”Manufacturing” and “Automotive” to further define the scope. Another way to find relevant articles is to ask colleagues for help.

The best way to find relevant literature is to start with looking into the leading journals (Webster & Watson, 2002). Therefore these journals are considered first. However, articles are not excluded based on the fact that they are not published in a leading journal. Another way to find relevant literature is to apply forward and backward search on the discovered literature. That means investigating if the article is referenced in future publications and which articles are citated in the article itself. The data evaluation should filter out all articles which do not answer the research questions. Non-scientific articles should be left out and the quality/reliability of each article is assessed.

Finally at the data analysis and interpretation stage, one attempts to make sense of the extracted data. In this case, the data is integrated. A qualitative synthesis is performed. For a qualitative literature review a method was first put forth by Ogawa & Malen (1991). This method is broken down into eight steps by Gall et al. (1996). Note that these steps parallel the basic steps in qualitative research. For a detailed description about the eight steps, please check the paper of Gall et al. The eights steps that are described in this paper are also used for the creation of this literature review.

The final step is the public presentation in which the literature review is drafted and presented. Randolph and Webster & Watson both express the importance of the reviewing and revision process. The review is audited by colleagues or supervisors to guarantee a proper literature review. Self-criticism is also of high importance to ensure that the literature review is of high quality and does not include commonly made mistakes.

The review first describes the Pearl Chain model, followed by the Just-In-Sequence method. Hereafter, applications of these two concepts in the automotive industry are discussed. So after reading this literature review, the reader knows more about the concepts Pearl Chain and Just-In-Sequence and how they can be implemented.

2. Pearl Chain Model

This chapter is used to learn more about the Pearl Chain model. First, the history is discussed. Hereafter three critical aspects of the Pearl Chain model are elaborated: Design, Planning and Control. In the corresponding sections, studies are explained which are related to these aspects. The section Pearl Chain Design presents methods on how to design and implement a Pearl Chain model. In the next section, Pearl Chain Planning, forecasting and how to plan personnel assignment of sequential assembly lines is discussed. Subsequently, Pearl Chain Control is elaborated. A couple of measures are given for determining the Pearl Chain performance and hedging methods are presented to retain control. Most of the studies in this chapter are related to the automotive sector. In the last paragraph of this chapter, Pearl Chain outside of the automotive industry is discussed.

2.1. History

Since 1997, the Mercedes-Benz A-Class has been produced in Rastatt based on the Pearl Chain concept (Weyer, 2002). At the same time, the implementation of the Pearl Chain concept among other manufacturers in the automotive industry has also been developing rapidly. The Porsche factory in Zuffenhausen established the target sequence at the beginning of the carcass construction. At Porsche the Pearl Chain sequence is maintained by 99% (Kahmeyer, 2002), according to their own statement. For Audi, the Pearl Chain concept is an element of the “new logistics concept”. Audi products in Neckarsulm can be used as a reference factory for the implementation of the Pearl Chain concept throughout the Volkswagen Group (Seeman, 2015).

The Pearl Chain concept is one of the latest lean methods from the automotive industry. Different applications of the Pearl Chain method in the automotive industry show that a stable order sequence can optimize production. Early order planning (taking into account related production constraints) aims to increase capacity utilization and provide a continuous production process (Copaciu, 2013). In addition, following the concept of Pearl Chain can stabilize the flow of information and materials. A “quiet” production process has a positive impact on all participants involved in value creation. An exemplary execution of the Pearl Chain method can lead to a reduction of 20% in product costs and a reduction of 50% in process costs according to the study of Unger & Teich (2009). The Pearl Chain concept is an adjusted strategy that helps to ensure the goal of lean production. Numerous studies have shown that in the era of global competition and rapid change, lean methods are the key to growth and survival.

2.2. Pearl Chain Design

Today, the automotive industry is characterized by an ever-increasing number of models, variants and equipment options. This continuous development leads to increased complexity. In order to successfully manage this complexity, many car manufacturers are using the Pearl Chain concept (Lehmann & Kuhn, 2017). In addition, the concept provides more opportunities for supplier and customer relationships. Through the Pearl Chain concept, suppliers can truly rely on quantity and order. On the customer side, orders can even be changed a few days before production starts (Klug, 2006). According to the definition of the Pearl Chain concept, the exact production sequence is usually determined by defining a so-called “frozen zone” 5-7 days before assembly (Wagner & Silveira-Camargos, 2012). After that, it is transferred to the supplier according to the order of the Pearl Chain. In the frozen area, customer changes are no longer easy to implement. Strict compliance with the production sequence enforces discipline in the production process. In between the manufacturing steps, the cars are sorted based on their production needs. The application of the Pearl Chain method in the automotive industry shows that a stable order sequence can optimize production. Early order planning aims to improve capacity utilization and provide a continuous production process. In addition, following the concept of Pearl Chain can stabilize the flow of information and materials.

A description of Pearl Chain design is given in “Pearl Chain Design for Synchronous Production” (Unger & Teich, 2009). This article first reflects the system categories of the original lean production system, and emphasizes the benefits of this concept from the pioneer model proven by the Japanese automobile company Toyota. In the context of synchronous manufacturing, the production system usually involves the following system category list, the elements of which have extensive coverage in lean projects:

- Design and Development
- Planning
- Operative Production
- Quality Assurance
- Procurement

Synchronous manufacturing is the direct opposite of traditional manufacturing methods, which are characterized by the use of economic order quantities, high capacity utilization targets and high inventory. In the process of transforming from this traditional environment to synchronous production, management changes in thinking and behaviour are required to match the manufacturing work of “reducing waste” or reducing costs. The Pearl Chain Manufacturing Organization provides assistance as an operational strategy to support lean, stable and robust processes to manage the supply network. The concept of the Pearl Chain can be described as a fixed-sequence production system in a supply chain that synchronises built-to-order production. It stands for a dynamic frozen point sequence planning and control system, involving system suppliers and distributors. Figure 1 shows the business process called the Customer Order Process (COP), which includes the following steps:

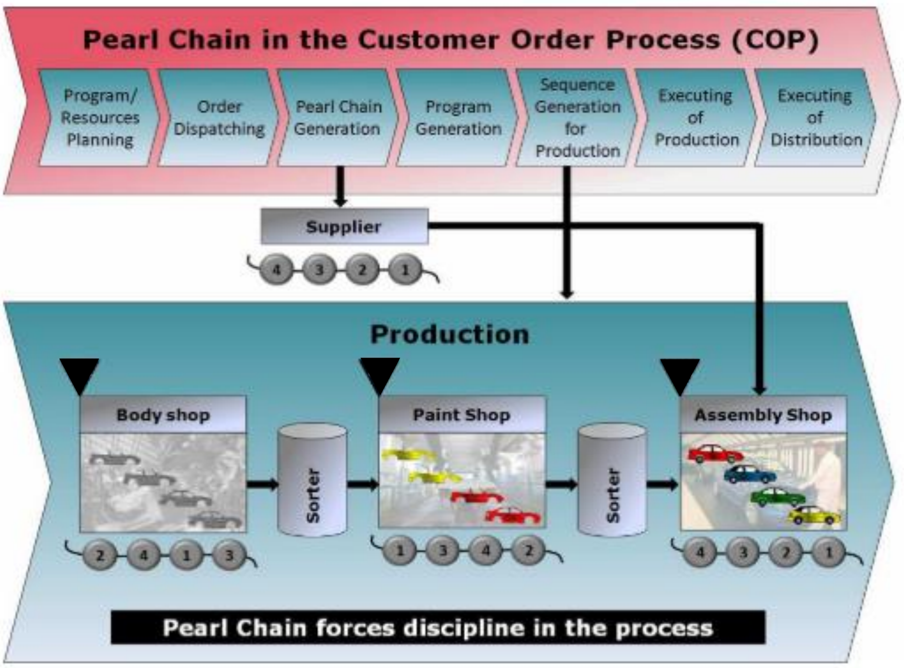


Figure 21: Pearl Chain in the Customer Order Process (Unger & Teich, 2009)

1. **Program/Resources Planning**: Rough planning of orders and resources for heavy items
2. **Order Dispatching**: Send orders in a stable date pattern a few weeks before distribution as a preview of suppliers
3. **Pearl Chain Generation**: Generate the order sequence of the assembly process a few days before the demand is needed and transfer it to the supplier
4. **Program Generation**: Plan the procedure for daily production of parts
5. **Sequence Generation for Production**: Generate anonymous sequences for all the manufacturing processes of parts
6. **Executing of Production**: Perform the production process in Pearl Chain
7. **Executing of distribution**: Perform the distribution process in Pearl Chain

In between the manufacturing steps from the body shop to the paint shop to the assembly shop the cars are sorted based on their production needs. The sorting is done because the body shop and the paint shop have a different optimized sequence than the assembly shop. At the beginning of the manufacturing phase, a status measurement point for sequence monitoring is installed. For a Pearl Chain, there are two important strategies: late-fit strategy and build-to-order (BTO) strategy. Late-fit means that the pearl must be as anonymous as possible to allow the supply network and the customer to obtain the highest flexibility. Its customer-specific personalization corresponds to BTO, which means that there is no forecasted transaction volume without actual customer demand behind it.

The key element comes from the frozen point plan. The basic idea of this concept is to treat the manufacturing sequence of automobiles as a chain of pearls, and to "freeze" the production date of the pearls in a defined but dynamically changing period of time before production, which is called the "frozen zone". The beginning of the frozen zone (FZ) is defined as d_{FZ} and ends with d_R (the specific date of the required (R) part or module). FZ dynamically changes according to the supplier's T_{PS} (production time) and T_{LS} (distribution time), and can be integrated into the Pearl Chain design, planning and management process. This condition can be formalized with Equation 1 (Unger & Teich, 2009).

Equation 1: Frozen Zone

$$d_R - d_{FZ} \geq t_{PS} + t_{LS}$$

Due to the expected cost reduction brought by outsourcing and the delivery of Just-In-Sequence production (JIS), in countries with lower labour costs, the trend of increasing distance from suppliers has led to the expansion of FZ. In Figure 2, the frozen area is shown inside the Pearl Chain.

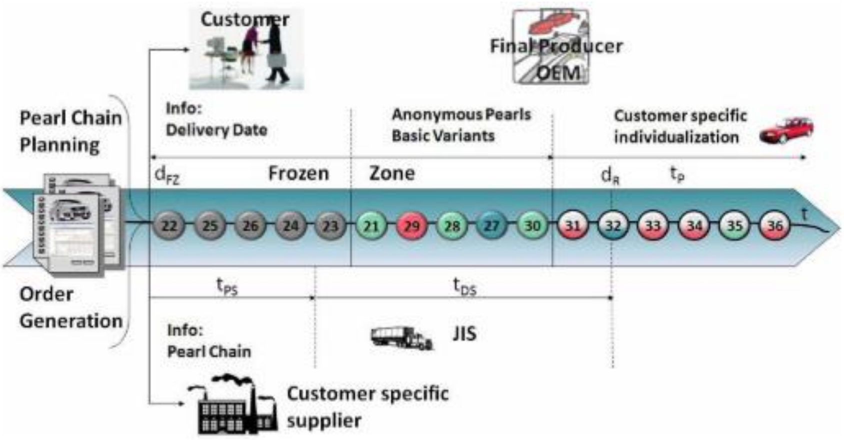


Figure 22: The Pearl Chain and the "frozen zone" (Unger & Teich, 2009)

The flexibility of the supply chain benefits from Pearl Chain management, not only for inbound logistics, but also for sequence planning through outbound plans. The background of the article of Unger & Teich (2009) lies in the automotive project between the University of Applied Sciences and the final producer Volkswagen Saxony in Zwickau, Germany (Casper, 2007). Since 2006, this factory has been in the pilot state for the implementation of the Pearl Chain Manufacturing Organization in 2007 during the first attempt to introduce a new Volkswagen integrated production system. A basic element of the production system is the Pearl Chain Manufacturing Organization, which covers the smoothing of production. It ensures that the workload is balanced over the planning periods and working places. Smooth manufacturing should bring process stability to the value-added network.

Unger & Teich (2009) outline the procedural model for implementing this Pearl Chain concept in general implementation guidelines. For the target operating structure, the lean-oriented Pearl Chain basically requires process redesign, process measurement and process control concepts to support agile but stable processes. The procedure model is shown in Figure 3.

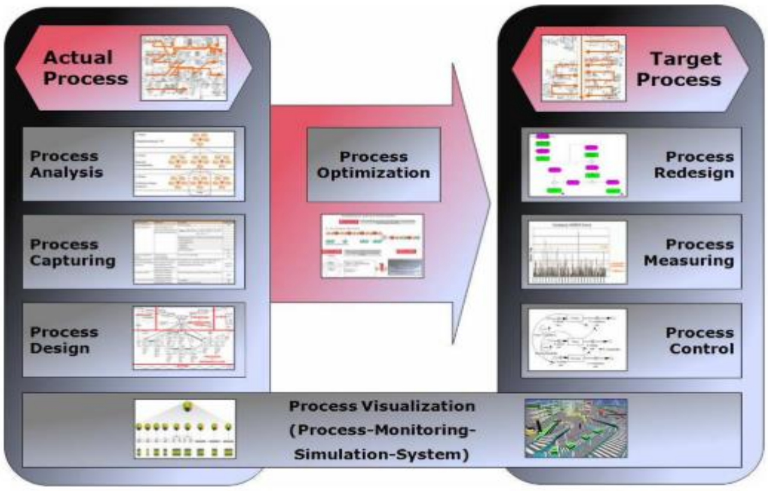


Figure 23: Procedure Model of Implementing Pearl Chain (Unger & Teich, 2009)

The Pearl Chain concept, as an adaptive strategy in synchronous production, helps to ensure lean goals in process optimization projects. The described process model helps to implement this Pearl Chain into a constantly changing process through the stability of control and measurement as a more streamlined guiding element.

2.3. Pearl Chain Planning

Mayrhofer et al. (2011) have written an article about the planning assistance of Pearl Chain forecasting and personnel assignment planning of sequential assembly lines. The European automotive industry is characterized by complex and customized products. This requires the most complex production planning to arrange various variants in a way that balances the deployment of workers and avoids production peaks. The focus of this work is to plan the final assembly of automobiles and parts in factories with higher labour intensity and lower degree of automation. Production planning is usually done periodically or “floating”. Assigning orders to weekly or daily time periods or shifts is called slotting (see Figure 4).

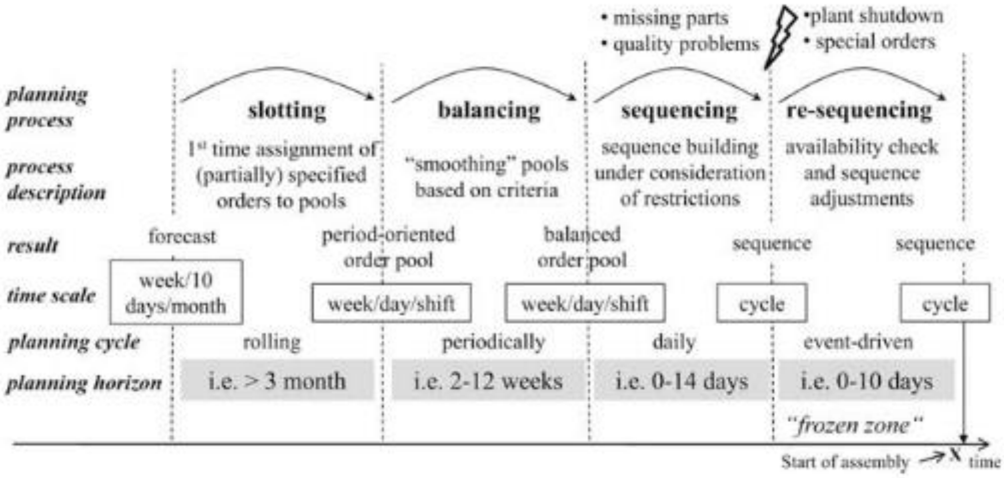


Figure 24: Planning process of a sequenced production line (Mayrhofer et al., 2011)

Periodic planning may continue slotting until a fixed sequence is given, which has a smooth effect on materials and capacitance-related standards. Taking into account more detailed restrictions, a single order can be moved to other production periods. The levelling of shifts is also called balancing. Implementation methods and sequencing goals may be different, leading to optimization models divided into three categories: level scheduling, mixed-model sequencing and car sequencing. The level scheduling is derived from the Toyota production system and is directed to the level of material requirements in the production sequence. Every time slot should contain the same amount of material requirements so that the workload becomes even. The purpose of mixed-model sequencing is to avoid overloading the capacity of the working stations. The overloads can be minimized by using detailed timing of the specific process duration for all the variants at each workstation. The purpose of car sequencing is to prohibit sub sequences of certain variables that are prone to overload through applying sorting rules, thereby avoiding overload (Williams, 1999). Therefore, a specific amount in subsequent variants is allowed to contain a certain option, otherwise overloading occurs. For example, the ratio rule for the option "sun roof" is 1:3, which means that only one of the three consecutive units can contain a sun roof. Most European manufacturers use car sequencing to avoid the complex data collection required for mixed-model sequencing.

Several personnel allocation schemes related to workstations can be distinguished. An employee can perform a task at one stop. Two (or N) employees can perform two (N) tasks at two (N) workstations. Another option is to use jumpers (reserve employees) at peak loads that cover X sites. When there is the threat of capacity overload, jumpers can be used for orders that have a high capacity demand of the production line, for tasks that only require specific skills that rarely occur or as replacement of absentees. Within the scope of the plan between the medium and short term (that is, the week before the start of production), the system has different reaction options, resulting in different actuation variables. On the premise that the production sequence is the target parameter, the possible changes to balance the shortage of personnel are:

1. Take advantage of the flexibility within the team
2. Deploy jumpers at relevant stations
3. Use variable personnel capabilities throughout the day
4. Adjust the personnel situation of the affected stations/shifts
5. Authorize temporary workload peaks and local compensating changes of sequence
6. Transfer work content between workstations

The planning process can be divided into pooling, sequencing, simulation and analysis. In an ideal (100%) assembly system working at full capacity, no performance-related losses occur. Cycle losses usually occur because the capacity of the station cannot be successfully solved by simply using task-oriented problems. Therefore, the cycle levelling of a station is a key indicator of average overutilization and underutilization during the planning period. Underutilization during the planning period (i.e. shifts) leads to positive results (τ_j>1), while overutilization causes negative cycle levelling (τ_j<1). See Equation 2 for the formula for cycle levelling (Mayrhofer et al., 2011). The formula can be used to determine if a specific working station needs more or less resources.

Equation 2: Cycle levelling

$$\tau_j = \frac{nT_j - \sum_{k=1}^{n} te_{kj}}{nT_j}$$

with: *j = index stations j =1 ... m*
k = index models k =1 .. . n
n = number of models
T_j = cycle time
te_{kj} = process time of model k at station j
τ_j = cycle levelling at station j

First, assign orders to all levels of the planning scope and minimize the team that assembles them (pooling). The second step of the sequencing determines the succession of orders. The given order of sequencing determines the process requirements of each station and each cycle. During a simulation, the staff assignments are carried out. Subsequently the tasks are executed in the simulation to see if the workload is balanced. In the final planning step, the staffing level in the simulation is compared with the staffing level from the pooling. If a backup pooler is used in the simulation, hot spots appear. This hot spot must be manually repaired by the user, as possible measures cannot be automatically assessed satisfactorily.

The input to the sequencing solution is the backlog of orders and the list of production constraints. Next is the generation of optimized sequences regarding the technical and personnel-related constraints. The sequence is used as the input for the simulation, and the input determines the feasibility of the sequence.

Assembly workers in the automotive industry show high flexibility, but this potential is often not used. An integrated staffing plan can take advantage of this flexibility, thereby increasing productivity. In addition, the ability to accurately predict the Pearl Chain brings various prospects. In short, the following advantages come from integrated personnel and production planning:

1. Higher transparency of personnel deployment and assembly process
2. Smooth capacity fluctuations and reduce “hot spots” and “cold spots” by as much as 30%
3. Increase employee capacity utilization
4. Proof of technical feasibility of production plan

2.4. Pearl Chain Control

The Pearl Chain concept (also known as the Pearl Necklace concept) has established itself as a production planning and control tool. Usually, the so-called “pearl necklace” is defined as the target sequence of pearls in the chain. In particular, pearl necklaces can represent the order of goods or services to be produced. In the automobile manufacturing industry, the “Pearl Chain concept” aims to physically maintain the defined target sequence from the beginning of the production plan to the final stage of production.

The key performance indicator Pearl Chain grade is based on a percentage to measure compliance with the target sequence determined on a specific date (Schröder & Tomanek, 2015). The Pearl Chain grade is calculated based on the difference between 1 and the average deviation of the target position (see Equation 3).

Equation 3: Pearl Chain Grade

$$\textbf{Pearl Chain Grade}\,[\%] = \left(1 - \left(\frac{1}{n}\sum_{i=1}^{n}|dot_i|\right)\right) * 100$$

$$if\ \left(\frac{1}{n}\sum_{i=1}^{n}|dot_i|\right) < 1;$$

$$\text{otherwise } Pearl\ Chain\ Grade = 0;$$

$$dot_i = deviation\ of\ the\ target\ position;$$

$$work\ order\ i = 1, \ldots, n.$$

Regarding the measuring and the control of the process stability, Unger & Teich (2009) propose the measure Sequence Excellence (SE). The formula is given in Equation 4.

Equation 4: Sequence Excellence

$$SE_{PC} = \frac{P_{\max} - P_{\min} + 1 - \left(\sum_{i=1}^{g} G_{Ri} + \sum_{i=1}^{g} G_{Fi} + \sum_{i=1}^{b} B_{Ri} + \sum_{i=1}^{b} B_{Fi}\right)}{P_{\max} - P_{\min} + 1}$$

SE_{PC} = Sequence Excellence
P_{max} = Pearl with the maximum sequence number
P_{min} = Pearl with the minimal sequence number
G_{Ri}/F_i = Gap in reverse/forward caused turbulences
B_{Ri}/F_i = Break in reverse/forward caused turbulences
g = Number of Pearls causing gaps
b = Number of Pearls causing breaks

Most automotive producers have implemented a built-to-order strategy to meet the demand for product variety. To avoid turbulence, automotive producers aim for two things: a JIS material flow and a “frozen zone” in the order sequence. Meissner (2010) introduces methods to assess and analyse production system stability. The aim is to ultimately improve the production flow control. Five main influences can be found on sequence stability:

- Process control effectiveness
- Material supply reliability
- Process quality
- Product planning stability
- Infrastructure and layout design of the plant

Different strategies are followed to cope with instability. Most of the automotive producers use physical re-sequencing by automated storage and retrieval systems or virtual re-sequencing by late order assignment to rearrange the sequence before the assembly starts. Most producers use a reactive approach instead of a proactive approach when sequence stability cannot be maintained. It is possible to measure sequence stability by assessing the position of an element in the planned sequence compared with the position in the actual sequence. A couple of measures are defined by Meissner (2010). Equation 5 and 6 give the Sequence Displacement and the Sequence Adherence.

Equation 5: Sequence Displacement

$$SD_i = output_i - input_i$$

Equation 6: Sequence Adherence with v as the amount of violations and n as the amount of elements

$$SA = 1 - \frac{1}{n}\sum_{i=1}^{n} v_i [\%]$$

For the Sequence Backlog the following algorithm should be applied:

- If the difference between the input-position and the output-position is bigger than 1, then the SB increases by this difference.
- If the input-position is smaller than or equal to the output-position, the SB shrinks by 1 (till SB=0).

An example of the Sequence Displacement and the Sequence Backlog is given in Figure 5.

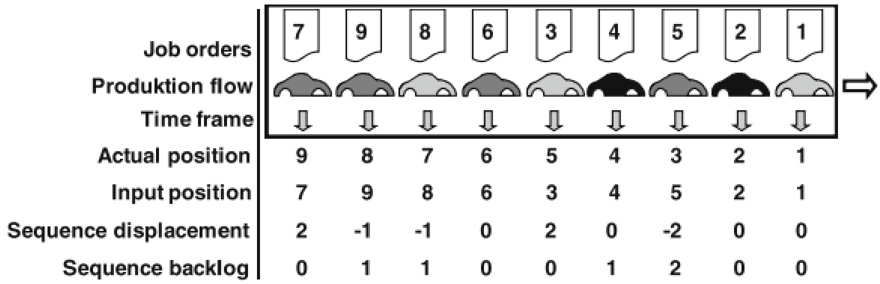


Figure 25: Example of Sequence Displacement and Sequence Backlog (Meissner, 2010)

The Pearl Chain Grade, the Sequence Excellence and the Sequence Adherence are also calculated for the example in Figure 5:

$$Pearl\ Chain\ Grade = 1 - \frac{1}{9} * (2 + 1 + 1 + 2 + 2) = 11.11\%$$

$$SE_{PC} = \frac{9 - (0 + 0 + 4 + 3)}{9} = 22.22\%$$

$$SA = 1 - \frac{1}{9} * 5 = 44.44\%$$

Equation 7 (Meissner, 2010) is based on Little's law. ct_{eff} is the effective cycle time, WIP^{en} is the inventory at the entry point and $SD_{rel,i}^{en-ex}$ is the relative Sequence Displacement between order exit and order entry.

Equation 7: Lead Time

$$LT_i = (SD_{rel,i}^{en-ex} + WIP^{en}) * ct_{eff}$$

Two main strategies exist to realize stable sequences in material flow:

- Control of sequence stability by eliminating process weaknesses and realizing high discipline
- Hedging against sequence instability by using re-sequencing methods

The focus of the Meissner's paper lies on the latter. Hedging is mostly done in the form of re-sequencing. It can be done either by re-sorting the car bodies physically or virtually. The order can be reassigned to another car body. This is usually done by exchanging orders for two cars. The material flow and the order flow are decoupled in that case. This is called flexible order assignment. The more different variants are processed, the lower the chance of finding an alternative car with similar characteristics. So one needs to either reduce the number of body variants or use a postponement strategy where features are added later in the process. Two ways of flexible order assignment can be defined. One can search for the best fitting car body in the process or the body in a sequence at a certain time is assigned to the earliest fitting customer order.

An alternative strategy is to introduce buffers. Buffers have the function of intercepting disturbances, overcoming physical distances and re-sequencing of car body sequences. Two main types of buffer systems can be distinguished: Automated Storage and Retrieval Systems (ASRS) and Mix-Banks (MB) as a set of parallel lanes. The task of the ASRS buffer with random access to each body is to rearrange the car bodies in ascending order, following the original order sequence. For a complete restoration, the size of the ASRS depends on the highest sequence displacement and therefore on the body with the greatest delay as shown by Inman (2003). If the car body cannot exceed the content of the entire buffer and must be stored first, then the required buffer size for doing a full re-sequence is defined by Equation 8.

Equation 8: Required buffer size

$$size_{SA=100\%} = SD^{+}_{max} + 1$$

The most used buffer type in automotive industry is Mix-Banks. Mix-Banks uses parallel lanes. In this way, the car bodies can be reordered according to the sorting goals. The lane selection policy is important for this type, together with the selection policy for the first car bodies on the lanes and the buffer configuration. The goal is to maximize Sequence Adherence and minimize the Average Sequence Deviation (ASD). Therefore, the cars need to be stored in ascending order and the lowest car numbers should be retrieved first. The SD of a body is reduced by the overtaken content of a buffer. For mix-bank buffers, a simulation is needed since the buffer size is variable. The rule for selection is that a lane is selected with the smallest positive difference between the planned sequence of the arriving car and the last car body of the lane. If that is not possible, an empty lane is selected or else the absolute difference is minimized. At retrieval, the car body with the lowest planned sequence position is chosen. For great lateness, it is possible to re-sequence car bodies by overtaking the whole buffer. It can be used when the planned sequence position of the car is lower than any of the other car bodies in the buffer.

Meissner (2010) compares the performance of the Mix-Banks buffer with the performance of the ASRS- and FIFO-buffer. From the research it can be concluded that the ASRS buffer performs the best, followed by the MB buffer with overtaking. The MB-buffer without overtaking performs slightly worse and the FIFO-buffer performs by far the worst. The optimal capacity level of the MB-buffer lies around 50%. With an overtaking lane it lies between 50% and 70%. The re-sequencing performance of the MB buffer increases with the number of lanes. So it is recommended to use as many lanes as possible. When combining virtual (flexible order assignment) and physical (buffers) re-sequencing the performance can be improved more. The flexible order assignment is simulated following the algorithm presented by Meissner et al. (2008). Virtual re-sequencing can compensate great lateness while physical re-sequencing focusses more on smaller lateness.

2.5. Pearl Chain outside the Automotive Industry

The performance of the Pearl Chain concept is also tested for hospitals by Tomanek (2018). Surgical therapy is the basic element of the hospital's value-added process. So far, the performance measurement of hospitals is mainly determined by the cost-oriented management of resources. An innovative approach to hospital operating room management is to comply with the defined pearl necklace. The research question of this article is whether it makes sense to transform the concept of Pearl Chain concept into operating room management from an efficiency perspective. The purpose of this article is to point out the possibility of transferring the Pearl Chain concept in a clinical setting. The purpose is to contribute to more effective operating room management in the future.

The adaptation of the Pearl Chain concept is based on the idea of a stable sequence of patients in the operating room on the day of surgery. It aims to improve patient satisfaction through reliable plans. The patient represents the pearls in chain to be operated. The target location was defined the day before the operation. On the day of the operation, the actual position is measured. Based on the theory, two hypotheses are proposed. With the help of case studies from five different hospitals, these hypotheses are evaluated.

H1: A low capacity utilization encourages a high Pearl Chain grade.
H2: A high capacity leads to swirls within the target sequence. The Pearl Chain grade drops.

At the inter-hospital level, the analysed hospitals cannot empirically prove that there is a negative correlation between the Pearl Chain level and capacity utilization. This result shows that the Pearl Chain level is not inconsistent with the efficiency of the hospital operating room (in the form of capacity utilization). Therefore, Pearl Chain grades can supplement rather than replace existing performance evaluations.

Based on empirical results, it is impractical to transfer the Pearl Chain concept to the operating room of the hospital as a whole. On the contrary, it is very convenient to make specific recommendations for the hospital taking into account factors such as the department and emergency rate. Only in this way can the Pearl Chain concept improve the efficiency of the operating rooms and improve patient satisfaction through a reliable planning.

2.6. Insights

A couple of insights can be derived from this chapter. The Pearl Chain model is a method that is widely used in the automotive industry. The origin of the Pearl Chain lies in Germany where it was introduced in one of the Mercedes plants in the 1990s. The Pearl Chain is defined by a stable order sequence which can be maintained by implementing a frozen zone. In the frozen zone no changes to the order sequence are allowed. By maintaining a stable order sequence, parts can be delivered via the Just-In-Sequence method. The advantages of this method are that inventories can be decreased which saves costs. Unger & Teich (2009) propose a framework on how to implement the Pearl Chain method for synchronous production. The presented framework can be used as a guideline for the implementation of Pearl Chain at TP. Planning is a big issue when implementing Pearl Chain. That is why planning assistance methods are presented in section 2.3. Mayrhofer et al. (2011) discusses planning assistance of Pearl Chain forecasting and personnel assignment planning of sequential assembly lines. Procedures are given which can help level the production and prevent overloads with the aim of using a high capacity utilization. Furthermore, a couple of measures are presented in section 2.4. These measures can be used as KPIs to assess the performance of the Pearl Chain model in simulations and in real life. Next to this, Meissner (2010) presents hedging methods which can help improve the process control. Lastly, to avoid tunnel vision, an application of Pearl Chain outside of the automotive industry is discussed. Tomanek (2018) presents the application of Pearl Chain in hospitals. Based on the results, it is not possible to transfer the Pearl Chain concept to hospitals as a whole. However, it can improve efficiency when applied correctly.

3. Just-In-Sequence Method

In this chapter, information is given about the Just-In-Sequence method. First, the history is discussed shortly. Hereafter, three main types of Just-In-Sequence literature can be distinguished. The first type focuses on the procurement and the supply chain. Subsequently, supply strategies are discussed, followed by how the JIS method can be optimized. At the end of this chapter, it is explained how the JIS method can contribute to a sustainable supply chain as sustainability is also an important aspect of Just-In-Sequence.

3.1. History

JIS as a delivery and logistics concept is often considered an extreme form or improvement of Just-In-Time (JIT), because it not only foresees the delivery of the right quantity and quality at the right time. JIS synchronises the production of suppliers and buyers to achieve sequenced parts delivery (SPD). The relationship between buyers and suppliers is tighter than in JIT delivery systems and the buyer is more dependent on the supplier. Next to this, JIS processes are more sophisticated. They require more process integration and higher standards. The historical development of JIS started at Daimler (Ulsamer, 1986) and Toyota (Mishina & Takeda, 1994). They started sourcing seats from external suppliers in sequence in the 1980s and 1990s, respectively. Today, JIS has become a widely used delivery concept in the automotive industry. For example, 62% of car parts are delivered in sequence for the Mercedes-Benz S-Class models (Graf & Putzlocher, 2004). This fact proves the wide application of JIS and how it has become the standard for the delivery of multiple vehicle modules.

3.2. Just-In-Sequence Procurement

Bányai & Bányai (2017) introduce how to model JIS supply of a manufacturing process. The logistics process integrates the supply chain of the production companies, from the procurement of raw materials required for the final product to the internal material processing of the factory, to the recycling of waste products, covering the four functional areas of logistics: procurement, manufacturing, distribution and recycling. Nowadays, Just-In-Time based material supply methods are becoming more and more important because they are flexible, reliable and they significantly increase cost efficiency. Several models can be found in the literature, which define the conditions that support the following decision: when is the need to change JIT supply to JIS (Wagner & Silveira-Camargos, 2011)? A few proposition are made. A minimal variety level of a module is needed if JIS sourcing is to be considered. Next to this, JIS sourcing is more advantageous for modules with a higher value. Furthermore, when the logistic complexity of a module is increased, the space requirement and the handling costs significantly decreases since a complex logistic process like JIS can help to ensure lower inventories. In the automotive industry, interest in JIS supply is increasing day by day. The advantages of JIS supply can be summarized as follows:

- Through improved transparency, it is easier to apply lean tools and solutions;
- Through high inventory turnover rate it is possible to improve operational efficiency;
- Strengthen the control of manufacturing, assembly and logistics;
- Reliably respond to customer needs;
- Through better supply chain management, make better use of resources including human resources;
- Reduce costs by avoiding excessive inventory (higher inventory turnover, reduced inventory holding costs, lower inventory damage costs).

The aim of the paper of Bányai & Bányai is to investigate the most important JIS supply methods. The contribution of this article is to describe models of JIS-based manufacturing supply systems, such as build-to-sequence (BtS), pick-to-sequence (PtS) and supply or ship-to-sequence (StS). With build-to-sequence, the required parts are produced in the order required by the customer's assembly plant. Sequential production of required parts can be insourced or outsourced. When pick-to-sequence is used, the required parts are sorted and picked up from the pre-production storage. This means that these supply solutions can be defined as in-plant supply that does not involve external suppliers. In terms of supply- or ship-to-sequence, the supply chain represents the vertical cooperation between network partners, such as suppliers, intermediate warehouses and customer production plants. The required products are sorted outside the manufacturing plant. Suppliers can participate in JIS-based supply if they have integrated IT solutions, segmented production and their procurement is synchronised with the production process. A model framework for the three different JIS methods is displayed in Figure 6.

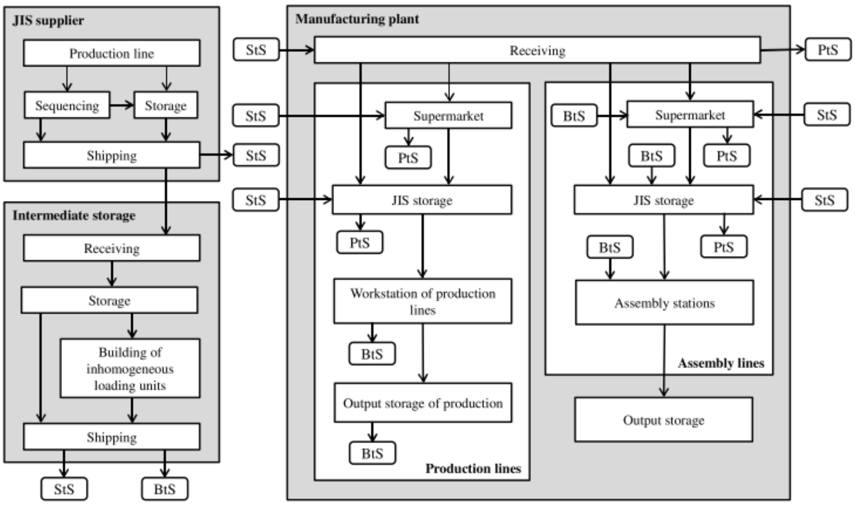


Figure 6: Model framework of JIS supply (Bányai & Bányai, 2017)

3.3. Supply Strategies

A way to handle JIS supply processes for a Pearl Chain in the automotive sector is to use milk runs (Conze et al., 2013). A milk run is a delivery method used to transport mixed loads from different suppliers to one customer. Milk runs and pick-up-tours controlled by Original Equipment Manufacturers (OEMs) like TP are transportation modes that are strongly discussed in the vehicle industry, however they are not implemented on a wider scale yet. In the automotive field, the supply concept can be divided into concepts with warehousing or without warehousing (Verband der Automobilindustrie, 2008). The concept of not requiring a warehouse is usually called the “Just-In-Time” concept or the “Just-In-Sequence” concept. The widely spread modes of transportation encountered in the automotive industry are direct transportation and consolidated freight. Direct transportation requires a direct link between the supplier and the OEM. Consolidated freight uses a hub where the suppliers can deliver their goods. Subsequently, the goods in the hub which contain goods from various suppliers are delivered to the OEM. Direct transport leads to lower freight costs, however inventories rise when the transport frequencies are low. Therefore, consolidated freight is mostly used for smaller suppliers. Direct transportation can be used for concepts with and without warehousing. Consolidated freight on the other hand can only be used for concepts with warehousing. Alternatively, materials can be collected and delivered in so-called milk runs or pick-up-tours arranged by the OEM, which are visualized in Figure 8.

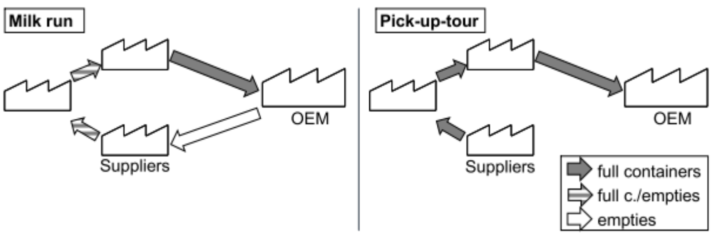


Figure 8: Milk run vs Pick-up-tour (Conze et al., 2013)

During the planning process, it is often necessary to decide whether to load individual parts on the current trailer or subsequent trailers. In order to ensure the safe coverage of the required parts provided by the supplier at the OEM production site, the appropriate basis for this decision is the time of the demand. A reliable milk run planning method requires more detailed information about the required time of the demand. Based on a fixed order sequence, reliable short-term forecasts of demand can be made. Currently, the Pearl Chain is only used for direct transportation. However, it can also be used for milk runs or pick-up-tours. Firstly, a system of freight rates designed for the milk run is important. Logistics data like volumes and weights should be available. The new freight rates have to be compared with the costs of direct transportation so that a cost saving potential can be determined. To avoid manual planning a powerful software tool is needed for this aspect. The developing of smart planning algorithms could be very useful for the implementation of milk runs. Routes should be designed between possible suppliers and the OEM to minimize the freight costs. Of course it is not mandatory to let the OEM arrange the routing. The carrier is predestined to do this job, so therefore input of the carrier should also be taken into consideration. The unloading of different products simultaneously could be difficult. Therefore arrangements have to be made between the carrier and the OEM on how to load and unload the trailer. For example, by only instructing the carrier or by giving an exact loading schedule.

In the automotive sector, the milk transport mode must compete with the consolidated freight concept and the direct shipping method. Compared with other modes, milk runs require more planning and coordination. However, case studies show that the potential can be increased under the right conditions. For the German freight area up to 60% of transportation costs can be saved. Additionally, inventory costs also lower, since the JIS concept is used. For direct transportation with low transport frequencies it is not feasible to lower inventories, while high transport frequencies increase the freight costs due to lower capacity of the trailers.

3.4. Optimization of the Just-In-Sequence method

JIS has been introduced to decrease inventories. Buffers are often identified as waste (muda). It is very inefficient to remove uncertainties in the production process by holding sufficient inventory for all the different parts and assemblies. Despite its benefits, a synchronisation is needed of production systems in a supply network. Numerous risks can be determined which should be optimized. Different risk sources in automotive supply networks with JIS are described by Wagner & Silveira-Camargos (2012). The risks sources are displayed in Figure 7.

The first risk source is supply-side risk. A primary risk driver from this source is supply base complexity, which is defined by T. Y. Choi & Krause (2006) as the degree of differentiation of the suppliers. That means the number of the suppliers and how they interrelate. Supply-base complexity has three dimensions (Choi & Hong, 2002). The number of direct first-tier JIS suppliers defines the horizontal complexity, which impacts the buyer's production process directly.

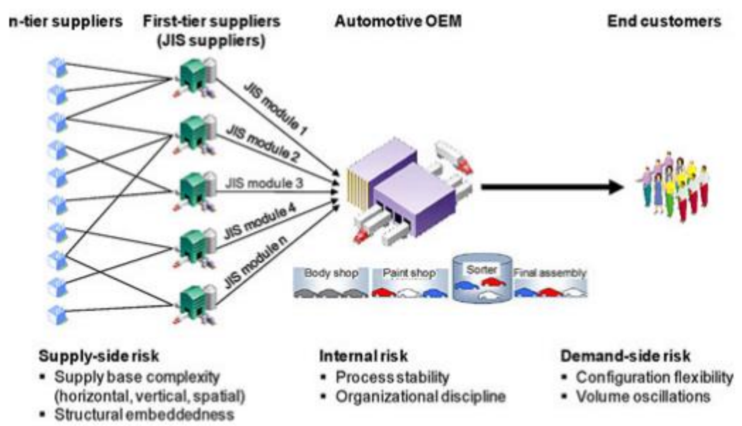


Figure 7: Risks sources for automotive supply networks with JIS (Wagner & Silveira-Camargos, (2012)

In case of disturbance, the impact can range from small rework to a stoppage of the assembly line. Vertical complexity is the number of suppliers in each tier. The reliability of second- or third-tier suppliers should also be of good quality, in order to get no disturbances. The third dimension is spatial complexity. That means the distances between the buyer's production site and their first-tier JIS suppliers. The closer the supplier, the smaller the risk. The second risk driver from the supply side is the structural embeddedness of supply networks. A buying firm has to understand the capability of their supplier. Knowledge is needed about the supply chain. The structure and the relationships should be analysed to get a better understanding.

The second risk source is internal risk. The related risk drivers are applicable to the manufacturing process. The two drivers are process stability and organizational discipline. Process stability is the extent to which a planned sequence can be maintained. Several automaker have introduced the Pearl Chain for this purpose. Resequencing is avoided, which improves the logistic efficiency. The goal is to minimize process uncertainty. This fact explains why autoproducers still use large buffers to hedge against these uncertainties. Organizational discipline and a reliable organization is key in lean production, since very often decisions are decentralized to floor employees. The responsibility of the individual increases when tasks are delegated. Therefore, more discipline is required from the entire organization. In tightly coupled systems, minor mistakes can lead to great disturbances. Discipline is even more crucial in these cases. The philosophy of a company should be fostered through the whole organization.

Two major risk drivers come from the demand side. Configuration flexibility is the first driver, which expresses the amount of freedom given to the end customer to make configuration modifications a few days before the start of the production. Volume oscillations is the second risk driver. It is not necessarily a threat. However, it can become a risk under certain circumstances. Because of the fact that all parties involved are tightly coupled, full flexibility is needed from all parties.

In the paper of Wagner & Silveira-Camargos (2012) risk management strategies are developed by doing a case study in supply networks. All the plants from the case study are located in Germany and they produce cars for Audi, BMW, Daimler, Ford, Opel, Porsche and Volkswagen. From the research a few propositions can be made. JIS is an established delivery concept in the automotive industry which has been growing and will continue to grow. Furthermore, JIS is not restricted to only short-distance deliveries. Most commonly automakers use external JIS deliveries from supplier parks and long-distance supplier plants, followed by short-distance deliveries. JIS can be used differently per producer. The main differences lie in the employed production control system, the supply network monitoring and the first-tier supplier management. Four archetypes could be distinguished: supplier-park purists, nearby sourcing, mixed JIS strategy and JIS trendsetters. The JIS trendsetters have the most complex supply network with higher spatial complexity and the most complex horizontal supply base.

Automakers most often face outages due to the supply network of the first-tier supplier, supplier quality problems and delivery delays. Internally, damage to the JIS modules in the assembly line and process failures in the paint shop are the most common causes of interruption of the JIS delivery systems. Risks of JIS deliveries are not detected to be higher compared to other delivery concepts such as JIT or on-stock due to the accurate planning of the sequenced delivery process. This is considered as the highest discipline in automotive logistics. After all, supply-side risk seems to be the major concern of automakers. However, their risk perception varies based on the used production control model and the market segment. From the surveys, it can be concluded that automakers use different tools to improve the JIS processes. The most tools focus on supply-side risks. The most automakers trust that their JIS suppliers can handle the supply-based complexity, since monitoring is only used in emergency cases. The quality of the buyer-supplier relationship betters the structural embeddedness of the supply network. Next to this, ensuring high process stability and promoting high-standard organizational discipline among employees is the key to reducing internal risks. Following configuration change rules set by automakers and improving the ability to respond to market changes is the key to managing demand-side risks. Four main recommendations are: improve supplier management with the help of KPIs, stabilize the production sequence, make the process transparent and manage the abnormality.

3.5. Sustainability

Papoutsidakis et al. (2021) express how JIS can help in the move towards a sustainable supply chain. Fierce competition, ever-changing market demands and ever-increasing customer demands have led to higher and higher requirements for customer preferences. In order to improve the efficiency of the supply chain, supply chain management practices have begun to develop towards a more frugal process approach. In order to achieve a high degree of flexibility and customer responsiveness, it is necessary to combine lean concepts and new technologies to quickly design new and improved functions in the workshop and other places.

Vehicle manufacturing can cause severe environmental problems before, during and after the production. Next to this, internationalization allows the company to focus on a long supply chain. This leads to wasted inventory costs and bullwhip effect, as well as higher overall costs. Lack of supplier support and cost sharing in R&D practices leads to an unsustainable supply chain. So by integrating the supply chain via the JIS method, one can effectively move towards a greener supply chain. The use of information technology tools is vital to support material flow management by suppliers directly to the automaker's assembly line. Today, the ideal trend is to ensure sustainability within the supply chain. Regulations, competitiveness and marketing are till now the mandatory reasons for measuring the performance of green supply chain management. It is elaborated that the use of JIS in combination with information technology tools can contribute to the sustainability goals of automotive producers.

3.6. Insights

The origin of the Just-In-Sequence method lies in the 1980s and 1990s at Daimler and Toyota where they started sourcing seats from external suppliers following this method. An integration of the supply chain is needed when implementing the JIS method. It requires a close collaboration between suppliers and buyers. Furthermore, a good IT structure is essential. When implemented correctly, a lot of inventory costs can be prevented. Nowadays, different frameworks exist on how to procure components according to the JIS method. Bányai & Bányai (2017) distinguish Build-to-Sequence, Pick-to-Sequence and Ship-to-Sequence. A careful consideration should be made on which JIS method to use. In section 3.3. Conze et al. (2013) present a way to handle the JIS supply processes for a Pearl Chain. By using so called milk runs, parts can be delivered via the JIS method and a high transport capacity can be maintained. Wagner & Silveira-Camargos (2012) identify the possible risks when using the JIS method. Evidently, all the possible risks should be taken into account and optimized. Recommendations on how to solve these risks are given. In the final section of this chapter Papoutsidakis et al. (2021) elaborate on how the JIS method can contribute to a sustainable supply chain, which is a hot topic at present.

4. Applications in the Automotive Sector

Chapter 4 discusses a couple of applications of the Pearl Chain model and the Just-In-Sequence method in the automotive sector. The first example is about a developed Supply Cockpit for Nedcar in Born. The second example discusses the paint shop of Porsche in Zuffenhausen. The third example elaborates on how the ERP system SAP is used at suppliers of automotive parts.

4.1. Nedcar Supply Cockpit

Nedcar in Born already successfully implemented the Pearl Chain. For Nedcar, a study is performed to design a Supply Cockpit to ensure JIS/JIT deliveries (Brenner et al., 2003). The planned Pearl Chain includes 7-day orders, with approximately 1,200 orders per day. The next day is planned in the early afternoon and then added to the end of the existing Pearl Chain. The Pearl Chain is also the basis for the planned inbound supply, and the supply must cover the demand generated by each pearl in the chain. There are a total of about 700 related JIS and JIT parts (60 pieces per pearl) and about 15,000 warehouse parts (1000-1200 pieces per pearl). All JIT or JIS parts are transported by truck from the supplier's site to NedCar's trailer yard, where they wait to unload the trailer for production. Each truck load can include a range of different parts from one or several suppliers. The actual configuration of the fully loaded truck is calculated based on the actual Pearl Chain and the actual coverage of the parts required. Five main system functions are required to plan and execute the business process of NedCar's production supply:

- Inventory accounting
- Coverage calculation
- Full truck load calculation
- Alert generating and monitoring
- System trailer yard call-offs

The system functions described are only applicable to JIT and JIS components. It does not consider warehouse parts. To calculate the coverages of all the relevant stock, the Supply Cockpit has to keep track of three different types of inventories: unloaded stock, yard stock and shipped stock. For Nedcar it is important to know how many stock is available of every different type. Due to the three inventory levels, it is possible to calculate three different coverage values, representing the time at which each inventory covers the pearls in the Pearl Chain. In other words, what part of the Pearl Chain can be covered by the present types of stock. The coverage levels can be calculated per part and per cluster of parts. An illustration of the coverage types is given in Figure 9. The colours represent different kinds of products.

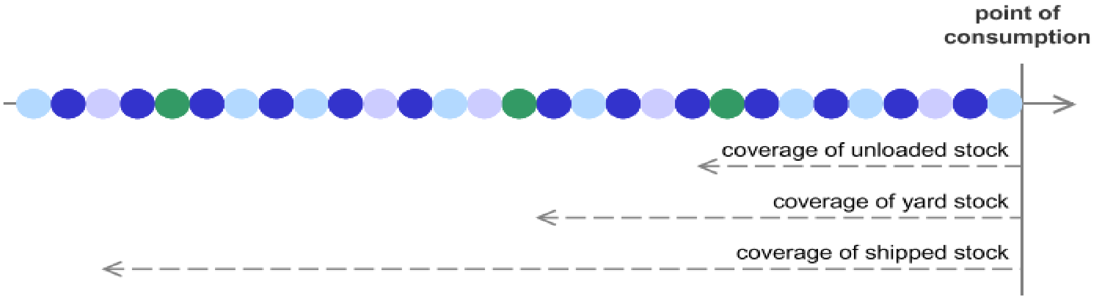


Figure 9: Different types of coverage (Brenner et al., 2003)

The full truck load calculation also has to be made. Specifically, it should be clear which parts are delivered by which carrier. The capacity of the carrier should of course be as high as possible to minimize costs. The Supply Cockpit starts the full truck load calculation with the first pearl not covered by shipped stock plus current inventory. Then, it goes along the planned Pearl Chain and fills up parts. Once a part is complete, another one is started. This process is executed separately for all parts belonging to the transport cluster. The calculation is finished, when the whole Pearl Chain is done and all part demand for the transport cluster is allocated. When filling up the truck, one should consider the weight and the volume of the parts. The time that a single truck load should be supplied is limited by the maximum supply time defined in the master data. The estimated number of new full truck loads per day is 120. Additionally, it is possible to calculate the expected call-off time when the parts should be moved from the yard to the factory. Also the arrival time at the yard and the departure time from the supplier can be calculated. When a truck load cannot be touched by the calculation program anymore, it is classified as “firm”. This process can be fully automatic. However, it would be wise to implement a feature so that the program can be manually overwritten.

Two types of alerts cans be distinguished. One is based on the current part coverages and one is based on the status of the trailers. A coverage alert is activated when the coverage level for a part drops below a minimum value. The threshold levels should be determined carefully. Each part should have a threshold level for the three different types of inventory. A trailer alert is activated when the material list of a trailer deviates from the order or when no material list is sent. Another reason for a trailer alert is when a recalculated truck/trailer has to leave the supplier.

Once the unloaded stock of a part drops below the corresponding replenishment level defined in the master data, the next trailer in the yard which carries that part is called off. In Figure 10 it is visualized how this process is managed.

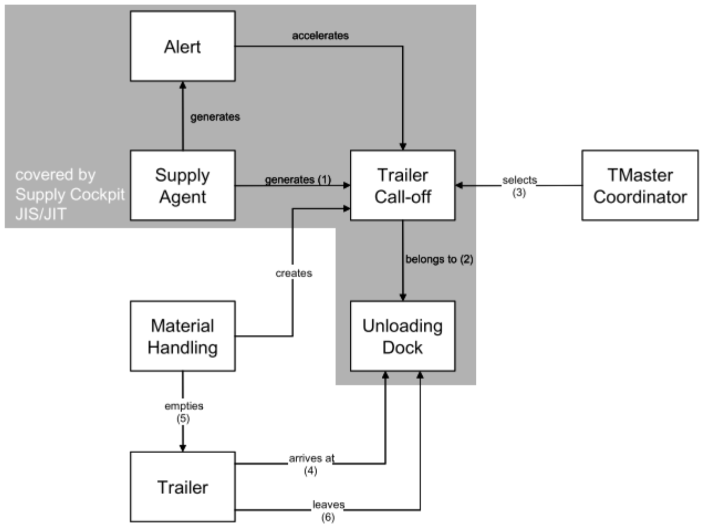


Figure 10: Call-off trailer yard (Brenner et al., 2003)

The Pearl Chain process is first tested on one assembly line. The other lines follow after the successful test. The basic premise of the implementation is 100% attention to the Pearl Chain philosophy. This means that if the car production does not exactly follow the sequence of the Pearl Chain, the results provided by the supporting system will not be correct. The rest of the document is used to elaborate on the system architecture. This part is more IT related and out of scope for the current project.

4.2. Porsche Paint Shop

At Porsche they implemented the Pearl Chain in their new paint shop (Scheffels, 2012) in Zuffenhausen. The reputation of Porsche sports cars manufacturer is legendary. However, only production engineering insiders know that its sister company Porsche Consulting provides advice to manufacturing companies around the world on how to improve their production processes. Therefore, people not only have high expectations for the quality of the paint process, but also for the organization of the material flow, which is always based on the principle of "stable Pearl Chain" at

Porsche. This means that activities must be carried out in the planned order throughout the production process. The body takes twelve hours to pass the paint shop. The only buffer zone is the bridge between the body building and the paint shop. As a result the company saves the space and time involved in operating a temporary storage area. For the paint shop, the result is that its work flow must be precisely coordinated with the entire automobile production process. It must also be able to respond flexibly to colour changes. Christian Friedl, Director of Body and Painting, said: “As we don’t have a painted body store, we must be able to change the top coat colour after every vehicle.”

The world's first E-Shuttle system was installed in Zuffenhausen. Each shuttle consists of three programmable axes, allowing the shuttle to follow its own dipping curve. The process is very technical. The body material should be taken into consideration during the paint job and the cavity sealing process happens with minimal waste of sealant. Then the body has to be cleaned before the paint job. This is done by a robot based blowing and suction process. Hereafter, the coating is applied by the Ecobell 3, an electrostatic high-speed rotary atomiser. The drying takes places in a building within a building, which leads to energy savings. The process is designed in a way that it produces as little waste as possible. A logical consequence is that a lot of energy can be saved.

4.3. SAP at Automotive Parts Suppliers

According to available data, more than 3,000 automotive companies worldwide rely on SAP software, and 77,000 cars are produced by SAP customer automotive companies every day. The ERP system affects the quality and efficiency of the logistics process to a large extent. They enable you to plan, coordinate, and control logistics flows related to material, financial, and information flows throughout the supply chain. The ERP system aims to provide seamless integration of processes across functional areas through improved workflows. Taking some of the largest (anonymous) auto parts distributors and manufacturers as examples, the article of Lorenc & Szkoda (2015) introduces Just-In-Time delivery and Just-In-Sequence delivery based on the SAP system. At present, JIT and JIS delivery are the latest solutions in customer logistics services in the automotive industry.

The finished product distribution system depends on the requirements set by the end customer. For delivery processing, auto parts manufacturers divide their customers into specific groups: Original Equipment Manufacturers, Original Equipment Services, and Automotive Aftermarket. Due to the timely delivery and the consequences of failing to meet its terms and conditions, it is important to divide customers into several groups. The parts delivered to OEM customers are the parts that go into mass production. Failure to deliver parts on time may result in production line shutdowns, and incur huge costs for suppliers. Parts for such customers are the number one priority. The second category is Original Equipment Service (OES) customers whose parts have been delivered to authorized service points of automakers. The problem of insufficient transportation can be compensated by negotiating with customers, but failure to provide timely delivery reduces the service rate. The main characteristic of this customer group is the ability to process orders, which change frequently when demand changes. Timeliness of delivery is a secondary issue. The third category is Automotive Aftermarket (AAM) customers, who provide individual customers with spare parts distribution on the market. For this group, timeliness is the most important factor in logistics services.

In a JIT delivery, there can be no shortage of goods. This type of delivery is only used by the OEM group of customers. Every customer regularly sends updated order schedules. The first one starts at the beginning of the year and covers a two-year time frame so that the master production schedule (MPS) can be drafted. The process of transporting goods in the SAP system starts with a VL10 transaction (transportation activity is due), entering the customer's code and the planned shipping date. The transaction displays all orders, delivery dates, inventory levels, and the quantity of materials to be shipped to customers on the relevant day. The system also communicates the shipping status delivered/delayed. JIT orders are processed using JITK transactions (Summarized JIT Calls Due for Dely). The entries in the system include the customer code and the organization date of the shipment.

Parts are delivered only when needed, thereby reducing OEM inventory. However, if the parts are delivered in order (JIS), the logistics work of the OEM can be further reduced. JIS means that suppliers pre-sort parts into bins so that assembly workers can take out these parts in the correct order defined by the production sequence. For example, at the BMW mid-size car plant in Dingolfing, it needs to handle more than 13,000 containers delivered by about 600 suppliers on more than 400 trucks every day (Piklik, 2014). JIS is a modern system that automates and optimizes key planning processes to deliver parts directly to the production line in the order predefined by the recipient. JIS eliminates the time required to reload parts delivered from the warehouse to the customer's production line.

The time for distributing the JIS timetable is divided into three periods: long-term forecast (12 months in advance), 15 working days before each shipment and 5 working days before shipment. The final JIS order arrives one day before shipment. During those 4 days, small changes to the order can be made. After receiving the order, the finished products are sorted into bins or containers in the system in the order assigned to them. The customer sends the order according to its pre-designed production plan and specifies the exact time when the part enters the production line. The first step in processing a JIS order is to check whether all codes of the ordered parts are in the correct format. Then, the parts are grouped in the order assigned to the unloading window. After the order is loaded into the system, a number is provided for the sorted shelves and then placed on the label of the container. The final stage of order processing is the order splitting between vehicles to optimize transportation costs. After that, the target recipient takes over the work, and all steps from receiving the parts to placing the parts in the appropriate racks and bins on the production line are performed.

The organisation of JIT and JIS distribution processes between an anonymous supplier and an anonymous customer of automotive parts is displayed in Figure 11.

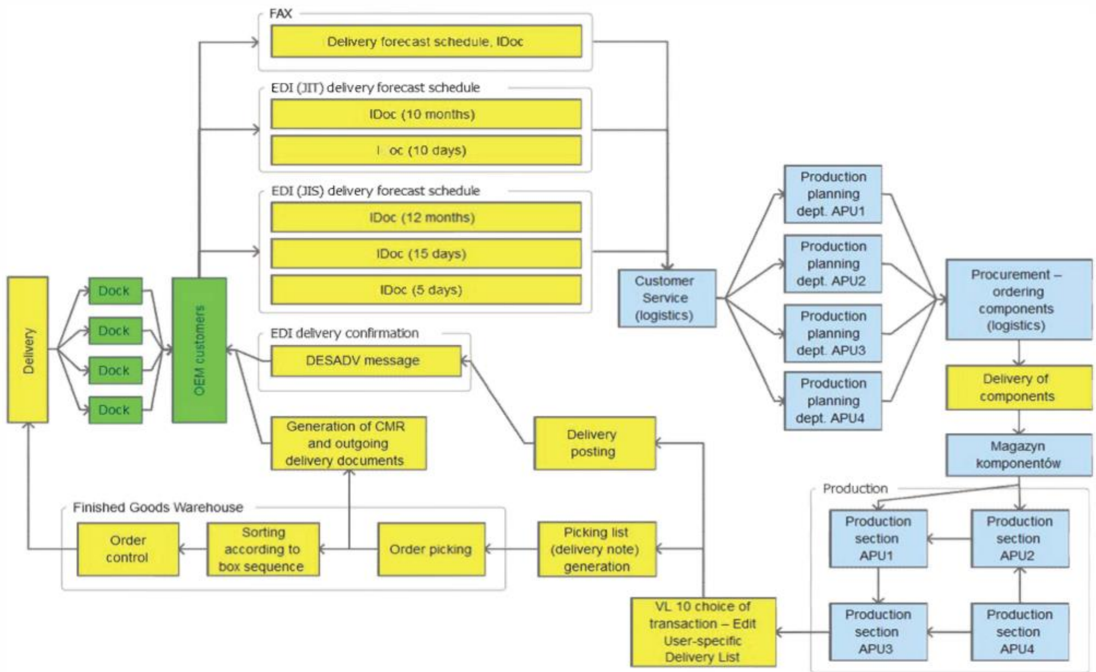


Figure 11: Functional diagram with JIT and JIS distribution systems (Lorenc & Szkoda, 2015)

Orders are placed in the form of IDocs (Intermediate Documents) via EDI (Electronic Data Interchange). Delivery problems are solved efficiently by quickly responding to complaints. Methods to ensure timely deliveries are the implementation of an order freezing period or agreements for building a stock level at the supplier before the due date. Another method is to maintain the ability to postpone the transport when parts are missing. The fourth method is for the supplier to hold extra stock. ERP systems are the unmissable link in the supply chain. By supporting JIT and JIS processes, SAP ERP benefits the whole organisation.

4.4. Insights

A lot can be learned from practical examples. The supply cockpit which Nedcar drafted (Brenner et al., 2003) gives great insights on how to implement a Pearl Chain model with JIS supply. One learns how the process should be adapted to fit the new model. By researching inventory accounting, coverage calculation, full truck load calculation, alert generating & monitoring and system trailer yard call-offs, great steps can be made towards a Pearl Chain model. These main system functions are also important for TP, since their business is very similar to Nedcar. Using practical examples of related businesses can be very beneficial. What can be learned from Porsche's paint shop in Zuffenhausen (Scheffels, 2012), is that innovative thinking improves the performance of the Pearl Chain. Porsche uses state of the art techniques which give them the capability to use meticulous planning. Their process is for a large part based on the use of shuttles and robots. These shuttles and robots ensure that nothing can go wrong during the process. In this way, it becomes possible to deliver perfect quality at every time. The process has been made flawless. The risks are minimized which ensures that the Pearl Chain sequence can be perfectly maintained. So if TP wants to implement the Pearl Chain, they should also consider to lift their production process to the next level by implementing new and more advanced techniques. The use of SAP at suppliers of Automotive parts shows that this ERP system can be very beneficial for the whole supply chain (Lorenc & Szkoda, 2015). SAP has great system functions, which flourish even more when the supply chain is integrated with the help of SAP. A whole procedure is given Figure 11, which could help TP and its suppliers during the implementation of Pearl Chain. A Pearl Chain model requires integration of the supply chain, so the given example in section 4.3. should be very useful for the rest of the project. Summarizing, if TP can map their system requirements, develop advanced production techniques and integrate its supply chain, the Pearl Chain future will be closer than ever.

5. Conclusion & Discussion

The conclusions of this literature review can be drafted by reviewing the research questions presented at the beginning of the report. The main question reads:

"What are the opportunities and challenges specific to automotive companies when implementing Pearl Chain with JIS deliveries?"

After reading the report, one should know how to start with the design of a Pearl Chain model. The framework of Unger & Teich (2009) gives a basic understanding of how a Pearl Chain process looks like and how to implement it. A frozen zone needs to be implemented to ensure that a stable order sequence can be maintained. The frozen zone makes sure that suppliers can deliver their goods according to the JIS method. The Pearl Chain model and the JIS method should go hand in hand. To maintain control of the Pearl Chain, a couple of measures (KPIs) are defined in this report. These measures can give an indication on the performance of the Pearl Chain. Next to this, planning methods are presented which can improve the Pearl Chain performance. Also hedging methods are presented to deal with unexpected situations. For developing a Pearl Chain model, it is important to design a lean process which involves meticulous planning, measurement and control.

Regarding the supply system, a decision needs to be made about the best JIS model for TP. Will it be best to use a Pick-to-Sequence, Build-to-Sequence or a Ship-to-Sequence model. All the alternatives should be carefully considered. Just-In-Sequence supply requires supply chain integration. Therefore more information about the production process should be shared with TPs suppliers. That is why an advanced IT structure is key for TP. The transfer to the SAP ERP system could be of use in the future. Milk runs or pick-up tours can be a good solution for the logistic processes of the JIS method. In that case, a truck does a tour where he visits multiple suppliers at once. When the truck is fully loaded he delivers the parts to the customer. This method ensures a high truck capacity and therefore a high efficiency with regard to the JIS deliveries.

A Pearl Chain production model in combination with a JIS supply system has a couple of benefits. First of all, the inventory can be decreased since goods are directly delivered to the production line and not stored in a warehouse. This saves inventory and damage costs. Next to this, unexpected overloads or shortages during the production can be prevented due to the fact that Pearl Chain production aids planning systems for the use of personnel and materials. Also a better control of the process can be maintained because the order sequence is predefined. Better planning and control lead to an improved production efficiency and a better process quality. It makes it possible for a company like TP to offer a wide variety of products to their customers. An additional benefit is that a sustainable supply chain can be developed. An efficient supply chain with less inventories is more sustainable. So from the literature, it is possible to conclude that the Pearl Chain method improves the process performance and lowers the production costs. By creating a simulation, the feasibility of the Pearl Chain model can be assessed. Different buffer configurations and buffer sizes can be used to test the performance of the process. When less buffers are needed, more components can be delivered according to the Just-In-Sequence method. The results of the research will provide clear recommendations for TP.

The challenges when implementing a Pearl Chain with JIS supply are defined by Wagner & Silveira-Camargos (2012). One of the challenges is that the supply chain needs a tight integration. TP has to work very closely with their suppliers. Production schedules should be shared with suppliers on predetermined periods. This requires a stable and well-functioning IT structure. The complexity of the supplier system also weighs in on these challenges. Internal challenges are process stability and organizational discipline. Process stability could be reached by investing into more advanced technologies. The research into these technologies cost much time and money. However, other cheaper methods can be used to reach process stability. Organizational discipline is the key for this. By implementing lean methods, a stabile process can be developed with a high organizational discipline. Another challenge can be how TP deals with order changes from customers. During which time period can customers change their order? This question applies to both the type of the product as the amount of the product.

The supply cockpit of Nedcar (Brenner et al., 2003) is a very straightforward example on how to implement a Pearl Chain model in the automotive industry. A part of it can be used for a Pearl Chain implementation at TP. The example gives main system functions which are also applicable to TP. The differences between the cases of Nedcar and TP should be investigated and the Pearl Chain model can be customized to TP's process. From the Porsche paint shop (Scheffels, 2012), it can be learned that TP still has room to develop their production process. A process which includes advanced technologies delivers a higher process quality. The process is more efficient and therefore it is easier to implement a Pearl Chain model. The use of the SAP program can also be beneficial to TP in order to improve the communication with their suppliers. SAP is an advanced ERP system which has proven its strength in the automotive industry. It can undoubtedly help TP to implement an organization wide JIS supply system. It is advisable to use more practical examples during the Pearl Chain and JIS implementation. When more practical examples from the automotive industry can be found, they are definitely worth looking at.

This literature review also knows its limitations. An unfortunate limitation is that no scientific literature could be found about a Pearl Chain or JIS application in the truck industry. Therefore only scientific literature about car production is used. However, this issue can be solved by performing some extra research about the differences between truck and car production. Furthermore, the implementation of Pearl Chain at a truck manufacturer has already proven to be successfully with MAN (Flexis AG, 2012). Unfortunately, no literature is published about this implementation. Another limitation is the fact that during the writing of this literature review, only global knowledge is gathered about the production process at TP. The rest of the project is used to learn more about the production process at TP. That means that new insights arise which will be included in the thesis report.

References

Bányai, T., & Bányai, Á. (2017). Modelling of just-in-sequence supply of manufacturing processes. *MATEC Web of Conferences*, *112*, 1–6. https://doi.org/10.1051/matecconf/201711206025

Brenner, M., Langner, W., & Sautter, M. (2003). *Blueprint Supply Cockpit JIS / JIT*.

Casper, B. (2007). Volkswagen fährt mit neuem Produktionssystem effizienter. *WIREG Aktuell*, *22*.

Choi, T. Y., & Hong, Y. (2002). Unveiling the structure of supply networks: Case studies in Honda, Acura and DaimlerChrysler. *Journal of Operations Management*, *20*(5), 469–493.

Conze, M., Sailer, T., & Günthner, W. A. (2013). *Combined Call-Off and Transport Control for Milk Runs Based on Order Pearl Chains in the Vehicle Sector. 11*(1 OP-Annals of the Faculty of Engineering Hunedoara-International Journal of Engineering. Feb2013, Vol. 11 Issue 1, p137-142. 6p.), 137. http://search.ebscohost.com/login.aspx?direct=true&site=eds-live&db=a9h&AN=86973050

Cooper, H. M. (1988). Organizing knowledge syntheses: A taxonomy of literature reviews. *Knowledge in Society*, *1*(1), 104–126. https://doi.org/10.1007/BF03177550

Copaciu, F. V. (2013). *Analyse der Wirkzusammenhänge in der Perlenkettenmethode in der Automobilindustrie*.

Flexis AG. (2012). *THE SUCCESS STORY OF THE PEARLCHAIN AT MAN*. Https://Www.Flexis.Com/En/Problems-We-Solved/the-Success-Story-of-the-Pearlchain-at-Man?Topic=24c3c8.

Gall, M. D., Borg, W. R., & Gall, J. P. (1996). Educational research: An introduction, 6th ed. In *Educational research: An introduction, 6th ed.* Longman Publishing.

Graf, H., & Putzlocher, S. (2004). DaimlerChrysler: Integrierte Beschaffungsnetzwerke. *Springer*, *2*, 55–71.

Inman, R. R. (2003). ASRS sizing for recreating automotive assembly sequences. *International Journal of Production Research*, *41*(5), 847–863.

Kahmeyer, M. (2002). Produktions-und Logistikkonzepte der Porsche AG. *VDI BERICHTE*, *1698*, 45–56.

Klug, F. (2006). Synchronised Automotive Logistics: An Optimal Mix of Pull and Push Principles in Automotive Supply Networks. *Logistics Research Network Conference Proceedings*, 187–191.

Lehmann, M., & Kuhn, H. (2017). In-Line Sequencing in Automotive Production Plants - A Simulation Study. *Operations Research Proceedings*.

Lorenc, A., & Szkoda, M. (2015). Customer logistic service in the automotive industry with the use of the SAP ERP system. *2015 4th IEEE International Conference on Advanced Logistics and Transport, IEEE ICALT 2015*, 18–23. https://doi.org/10.1109/ICAdLT.2015.7136584

Mayrhofer, W., März, L., & Sihn, W. (2011). Planning assistance for pearl chain forecasts and personnel assignment planning of sequenced assembly lines. *CIRP Annals - Manufacturing Technology*, *60*(1), 481–484. https://doi.org/10.1016/j.cirp.2011.03.044

Meissner, S. (2010). Controlling just-in-sequence flow-production. *Logistics Research*, *2*(1), 45–53. https://doi.org/10.1007/s12159-010-0026-5

Meissner, S., Kammermeier, F., & Grinninger, J. (2008). Stabilisierung des Auftragsabwicklungsprozesses durch flexible Auftragszu- ordnung. *ZWF*, *103*(12), 893–897.

Mishina, K., & Takeda, K. (1994). *Toyota Manufacturing USA, Inc.*

Ogawa, R. T., & Malen, B. (1991). Towards Rigor in Reviews of Multivocal Literatures: Applying the Exploratory Case Study Method. *Review of Educational Research*, *61*(3), 265–286. https://doi.org/10.3102/00346543061003265

Papoutsidakis, M., Michael, S., Sfyroera, A., & Priniotakis, G. (2021). Just-in-Sequence Technologies to Boost Automotive Supply Chain Effectiveness. *Open Journal of Applied Sciences*, *11*(01), 9–19. https://doi.org/10.4236/ojapps.2021.111a002

Randolph, J. J. (2009). A guide to writing the dissertation literature review. *Practical Assessment, Research and Evaluation*, *14*(13).

Scheffels, G. (2012). The Pearl Chain Logistics Concept. *JOT-International Surface Technology*, *5*(2), 18–21. https://doi.org/10.1365/s35724-012-0077-z

Schröder, J., & Tomanek, D. P. (2015). Wertschöpfungsoptimierung von klinischen Unterstützungsprozessen. In H. Woratschek, J. Schröder, T. Eymann, & M. Buck (Eds.), *Wertschöpfungsorientiertes Benchmarking: Logistische Prozesse in Gesundheitswesen und Industrie* (pp. 123–137). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-43718-6_10

Seeman, C. (2015). Alles folgt der Perlenkette. *DVZ*.

T. Y. Choi, & Krause, D. R. (2006). The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation. *Journal of Operations Management*, *24*(5), 637–652.

Tomanek, D. (2018). How the Pearl Chain Concept Can Improve the Performance of Operating Theaters in Hospitals: Results of an Empirical Study. *Business Logistics in Modern Management*, *18*, 605–616.

Ulsamer, W. (1986). Daimler-Benz–Keiper-Recaro—Zusammenarbeit am Standort Bremen [Daimler-Benz–Keiper-Recaro—Collaboration at the Bremen production site]. *Handelsblatt*, *198*, 23.

Unger, K., & Teich, T. (2009). Pearl chain design for synchronous production. In *IFAC Proceedings Volumes (IFAC-PapersOnline)* (Vol. 42, Issue 4 PART 1). IFAC. https://doi.org/10.3182/20090603-3-RU-2001.0534

Verband der Automobilindustrie. (2008). Standardbelieferungsformen der Logistik in der Automobilindustrie. *VDA-Empfehlung*, *5010*.

Wagner, S. M., & Silveira-Camargos, V. (2011). Decision model for the application of just-in-sequence. *International Journal of Production Research*, *49*(19), 5713–5736. https://doi.org/10.1080/00207543.2010.505216

Wagner, S. M., & Silveira-Camargos, V. (2012). Managing risks in just-in-sequence supply networks: Exploratory evidence from automakers. *IEEE Transactions on Engineering Management*, *59*(1), 52–64. https://doi.org/10.1109/TEM.2010.2087762

Webster, J., & Watson, R. T. (2002). Analyzing the Past to Prepare for the Future: Writing a Literature Review. *MIS Quarterly*, *26*(2), xiii–xxiii. https://doi.org/10.1.1.104.6570

Weyer, M. (2002). Das Produktionssteuerungskonzept Perlenkette und dessen Kennzahlensystem. *Karlsruhe: Helmesverlag*, *1*.

Williams, H. P. (1999). *Model Building in Mathematical Programming. 3rd ed.*