Professional MBA
Automotive Industry

Analysis of production planning and control systems for automotive powertrain assembly lines concerning the level of decentralization in the context of Industrie 4.0

A Master's Thesis submitted for the degree of
"Master of Business Administration"

supervised by

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Affidavit

I, **PETER BRAUN**, hereby declare

1. that I am the sole author of the present Master's Thesis, " ANALYSIS OF PRODUCTION PLANNING AND CONTROL SYSTEMS FOR AUTOMOTIVE POWERTRAIN ASSEMBLY LINES CONCERNING THE LEVEL OF DECENTRALIZATION IN THE CONTEXT OF INDUSTRIE 4.0", 83 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 15.09.2014

Signature

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List of Abbreviations

APS	Advanced Planning System
BOM	Bill of Material
BTO	Build to Order
BTF	Build to Forecast
CIM	Computer Integrated Manufacturing
CPS	Cyber-Physical System
CPPS	Cyber-Physical Production System
EDI	Electronic Data Interface
ERP	Enterprise Resource Planning
ICT	Information and Communication Technology
IoT	Internet of Things
IT	Information Technology
JIS	Just in Sequence
JIT	Just in Time
KPI	Key Performance Indicator
OEM	Original Equipment Manufacturer
PLM	Product Lifecycle Management
PPC	Production Planning and Control
MES	Manufacturing Execution System
MPS	Master Production Schedule
MRP	Material Requirements Planning
WIP	Work in progress

Abstract

The motivation to address the subject of Industrie 4.0 developed during the lectures of Professor Sihn, who mentioned Industrie 4.0 as a promising opportunity for manufacturing companies. As the MBA program is focused on automotive industry and logistics is a core theme of the program, the idea was born to investigate production planning and control (PPC) in an automotive plant in context with Industrie 4.0. The expectations of Industrie 4.0 concerning the increase in productivity and mastering of complexity through the introduction of cyber-physical systems and the internet of things in the manufacturing world are high. The decentralization of decision making in cyber-physical production systems is propagated as a key function to improve the fulfillment of the logistic objectives.

The master thesis introduces Industrie 4.0 and production planning and control in terms of the degree of centralization and autonomous control. The evaluation of the degree of decentralization is approached to be measured in terms of autonomous control, based on the use case and the application of production planning and control for an automotive powertrain plant. The research is focused on short-term scheduling and sequencing. The current state of the PPC tasks are evaluated by SWOT analysis and a possible target concept in terms of Industrie 4.0 is outlined.

The current state of PPC is a hybrid system, where the assembly line is planned centrally by the PPC department and the upstream component lines are planned retrograde at the shop-floor in mutual cooperation with the PPC department. The level of autonomous control of the system elements is rated as low. The opportunities that are expected with Industrie 4.0 technologies increase with the importance of the availability of real-time data. The outlined manufacturing system is based on lean principles and flow lines, as they are set up today. The application of cyber-physical systems enhances the production planning and control systems to optimize the models of MES/APS tools to create a self-optimizing real-time model of the production that can optimize the fulfillment of the logistic objectives even in case of disruptions, based on analysis of historical data of disruptions.

Keywords: Industrie 4.0, production planning and control, decentralization, automotive industry, assembly line

1 Introduction

The automotive industry and in particular the European car market are under high pressure since the last economic crisis and because of trends such as demographic change, globalization and the resource conservation. New and attractive products have to be brought in permanently decreasing intervals and in increasing variety in a cost efficient design to the market. An appropriate production planning and control system (PPC) is the key element to meet the increasing complexity and demanding requirements of the markets (Sihn Wilfried, 2013, p. 61).

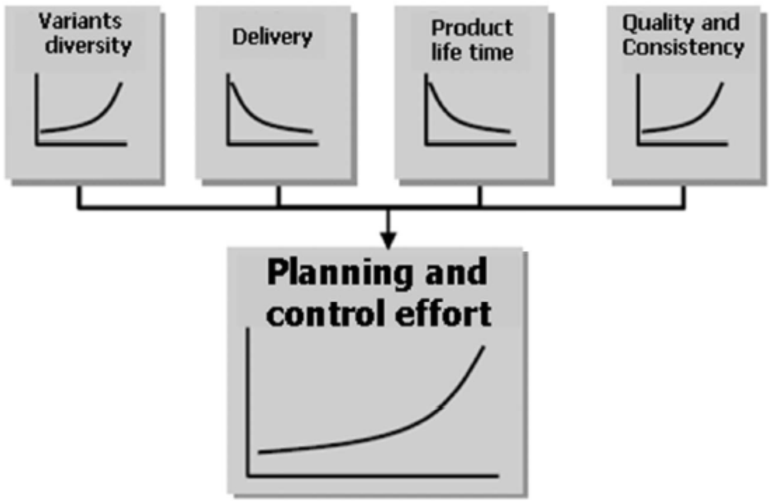

Figure 1 : Necessity for PPC (Sihn Wilfried, 2013, p. 61)

Today production planning and control systems are executed with a mixture of centralized and decentralized tools. Deterministic, centralized information and communication technology systems (ICT) support the planer to determine the production schedule for the assembly line, based e.g. on shipment due date and minimized setup costs. The upstream manufacturing areas can be planned and controlled either by the centralized system or a decentralized approach. For the decentralized PPC the manufacturing area has to schedule autonomous, e.g. based on an adequate forecast of assembly line requirements.

Since the deterministic ICT system cannot predict the future, the determined plan and the shop floor reality always start to deviate. Drivers for that behavior can be insufficient calculation models or impacts of short-term changing customer demands, disruptions and material availability (Kletti J., 2006, p. 147).

The governments in Germany and the US propagate a trend of advanced manufacturing. In Germany, and as well in Austria, the advanced manufacturing strategy is propagated under the title "Industrie 4.0", based on the high tech strategy initiative of the German government (Holdren J.P. et al., 2012), (Bundesministerium für Bildung und Forschung (BMBF), 2012, p. 52).

The key focus of Industrie 4.0 is to merge modern ICT with classic industrial processes to create a smart production, which sets new standards in flexibility, mastery of complexity and resource efficiency and bringing more transparency into production. The core element of this paradigm shift is a cyber-physical system (CPS, explanation see chapter 2.1.2), which enables machines and facilities, the material, products and the processes to build ad-hoc connected networks and real-time availability of data. This technology enables the formation of adaptive, self-optimizing, decentralized controlled production and logistic networks.

The hypothesis and expected benefit of decentralized self-control (autonomous control) is that in case of increasing system complexity in combination with many disorders self-control causes an improved achievement of logistical targets for the entire system. (Hülsmann M. and Windt K., 2007, p. 3)

The application of CPS technology on a production system creates a cyber-physical-production-system (CPPS) that will optimize the process flow and schedule decentralized and in real-time. The expected added value of decentralized production planning and control is to optimize the four competing objectives of the target system of production planning and control, see figure 2.

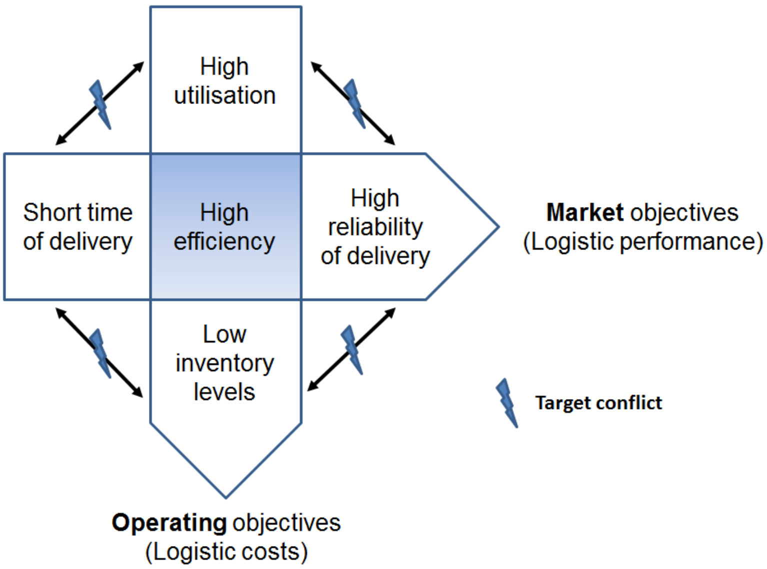

Figure 2: Target System of Production Planning and Control (Sihn Wilfried, 2013, p. 62)

The objectives short lead time of delivery and reliability of delivery are derived from the quality of the logistical performance, which is determined by lead-time and due-date performance. They represent the market-related objectives. The profitability of the manufacturing process is influenced by loading of the facilities and the work in progress (WIP). The operating objectives high utilization and low inventory levels represent the operating objectives of the target system of PPC.

1.1 Research focus and problem

This master thesis analyzes the current state of a powertrain manufacturing plant concerning the degree of decentralization of production planning and control by defining a concept of evaluation of the current state and the development of a scenario of a future state based on the application of CPS for decentralized autonomous production planning and control. Main focus will be the PPC elements of short term scheduling and sequencing.

The increasing variety of vehicles, including their options, has created a high number of powertrain variants, which lead to a daily challenge of production planning and control for automotive powertrain plants. Short term changes in demand, shortfalls in material and disruptions on the shop floor lead to deviations of the current state of production to the planned state. Corrections of the planned schedule lead to a high effort in communication and scheduling in all involved departments. It is estimated, that the introduction of Industrie 4.0 will support the PPC with a real time picture of the current state of production, preprocessed data for decision making processes and decentralized decisions concerning the processing of orders through the production.

1.2 Research questions and aim

Based on the research problem and the relating research focus, the central research questions are following:

- What is the added value generated by decentralized production planning and control systems in the automotive industry based on the example?

- How decentralized are production planning and control systems currently designed and developed in the automotive industry?

- How could the decentralized design of a production planning and control system for a powertrain assembly plant of the automotive industry look like?

The aim of this master thesis is to evaluate the potential of a decentralized production planning and control for an automotive powertrain plant and outline a possible design of decentralized PPC in terms of Industrie 4.0.

1.3 Methodical approach

The planned approach to elaborate this master thesis and to answer the research questions is divided into two key parts:

Part 1: Theoretical Framework

The theoretical framework, based on literature study, comprises the concept of Industrie 4.0 and its core elements, an introduction to Production planning and control, the methods in literature concerning the evaluation concepts for the assessment of decentralized control and the concepts of decentralized PPC in terms of Industrie 4.0. Specific examples of PPS concerning scheduling and sequencing will be explained. This part should provide the foundation for the reader of this thesis for the empirical investigation and the final recommendation.

Part 2: Case Study and Empirical Investigation

The second part starts with a case study of the Short term scheduling and sequencing strategies at an automotive powertrain plant focused on the centralized and decentralized perspective of PPC. Literature concerning the scheduling and sequencing strategies and problems is discussed. The structure will follow the Short term scheduling and sequencing strategies of Vehicle assembly plants because of the high variety and complexity of vehicle assembly. In case of expected differences between powertrain assembly, respective manufacturing, and vehicle assembly the differences will be discussed.

The methodical approach for the empirical investigation of the degree of decentralization is conducted by qualitative interviews with employees of the production planning department and the production department. The focus of this on the evaluation of the degree of centralization and the potentials of decentralized planning. The model of evaluation of the degree of autonomous control will be applied to define the degree of decentralization in the different tasks of PPC. The current challenges and requirements for a PPC in terms of Industrie 4.0 will be considered. Based on the analysis, the potentials for a recommended state of decentralization for the tasks of master production scheduling, production sequencing and re-sequencing will be determined.

The methodical approach of the master thesis is outlined in Figure 3.

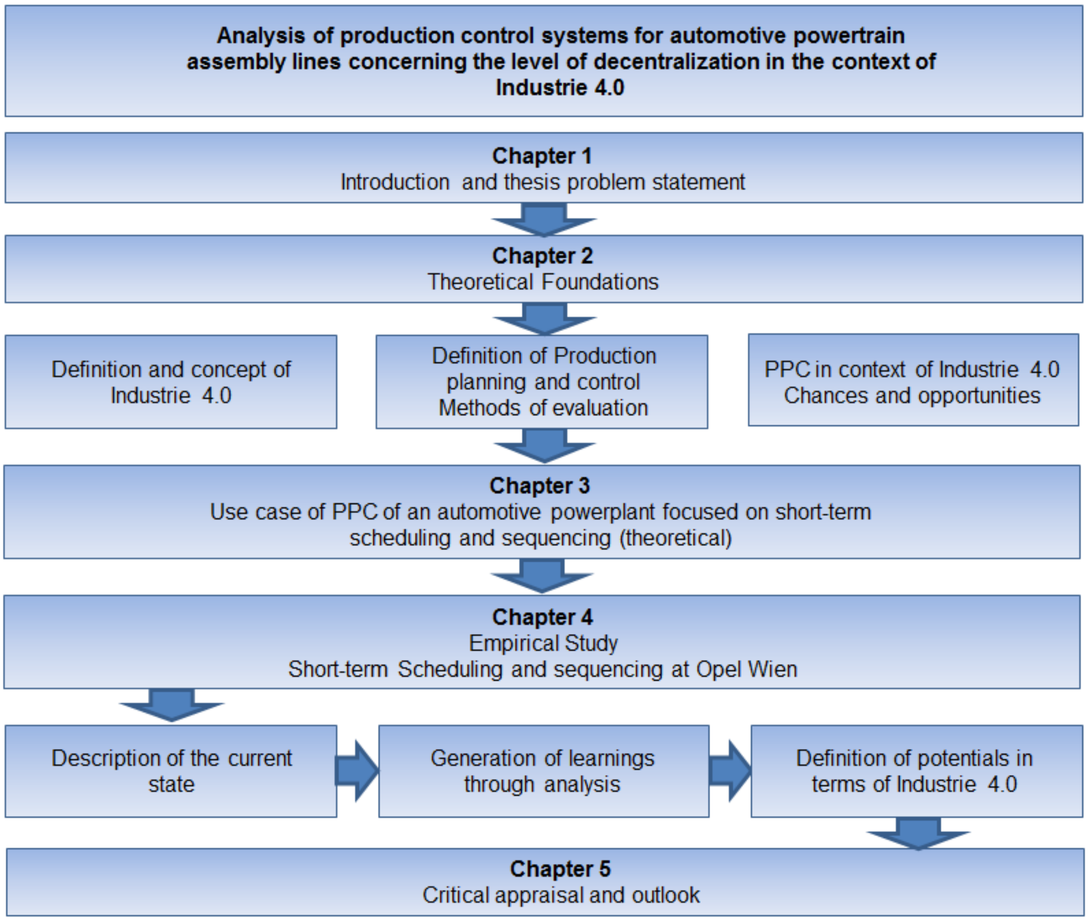

Figure 3: Methodical approach of master thesis

2 Theoretical foundations

The theoretical framework will introduce into the reader into the basic idea and elements of Industrie 4.0, give an introduction into production planning and control , and will illustrate exemplary the potentials of PPC in terms of Industrie 4.0.

2.1 Industrie 4.0

This chapter introduces into the idea and the core elements of Industrie 4.0 to outline the potentials of this vision. The paradigm change of Industrie 4.0 is a potential enabler for new approaches concerning production planning and control.

2.1.1 The vision of Industrie 4.0

The governments in Europe and USA currently accelerate a trend towards advanced engineering, which is in Germany propagated under the title "Industrie 4.0", starting from an initiative of the German government. The motivation of the German government is to advance the leading position of the German manufacturing industry and the German manufacturing equipment industry. The first three industrial revolutions introduced mechanization, electricity and Information and Communication technology (ICT) into the manufacturing processes. The propagated fourth industrial revolution will connect the real world and virtual world to create new production and process methods. Industrie 4.0 implements Cyber-Physical Systems (CPS) as well as the Internet of Things and Services into the manufacturing environment (Kagermann H. et al., 2013, p. 13).

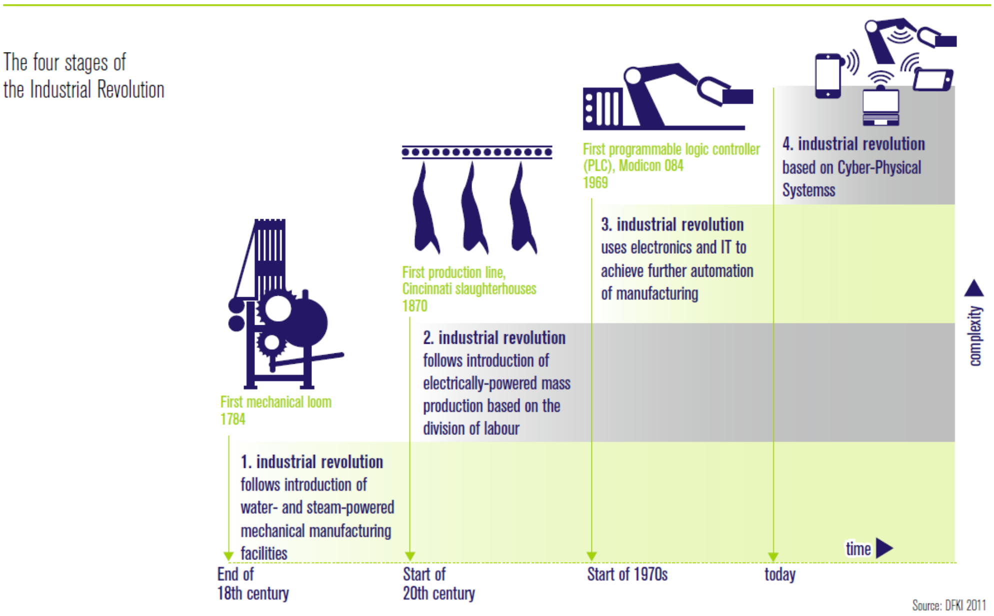

Figure 4 : The four stages of the Industrial Revolution (DKFI, 2011, cited by Kagermann H. et al., 2013, p. 13)

The integration CPS and the Internet of Things allows to establish smart factories, that are capable of managing complexity, are less sensitive against disruption and are able to produce the goods more efficiently. In the framework of Industrie 4.0 all systems, machines, products and workers are connected and share and use real time data to optimize the production processes. The real time, all-embracing and intelligent connection of all these factors is the core element of Industrie 4.0. A change of paradigm concerning the planning and control of value streams is expected. In contradiction to today's top down control, Industrie 4.0 is distinguished by a decentralized, self-organized control behavior. Objects like products have active or passive intelligence e.g. by embedded systems or identification methods like RFID. They can actively control their production processes by real time data and can decide e.g. in case of disruptions, which machine can handle the next process step. An up-to-date real time picture of the real production world is available in the virtual world. In contrast to the idea of CIM (Computer integrated Manufacturing), the integration of the human person is one of the focuses of Industrie 4.0. The preprocessed real time data assists the worker to fulfill his task and delivers accurate data for decision making (Kagermann H. et al., 2013).

From the economic point of view, the expectations concerning Industrie 4.0 are high. E.g. for automotive industry, where the main fields of application are anticipated in production and logistics, a cumulated increase in productivity of 20 percent until 2025 is expected (Bauer W. et al., 2014, p. 32).

2.1.2 Core features of Industrie 4.0

The promoters group Industrie 4.0 has defined three fields of action for the application of the Internet of Things for manufacturing (Kagermann H. et al., 2013, p. 20):

- horizontal integration through value networks
- vertical integration and networked manufacturing
- End-to-end digital integration of engineering across the entire value chain

The realization the internet of Things is based on Cyber–Physical technology and the Cyber-physical systems, where a short description will be given.

Horizontal integration through value networks

As defined by the promoters group Industrie 4.0, the horizontal integration refers to the integration of today's various IT systems used in different stages of manufacturing and business planning process that involve the exchange of material, energy and information within the company and between several companies. The aim of this integration is the establishment of an end-to-end solution across the entire value chain (Kagermann H. et al., 2013, p. 31).

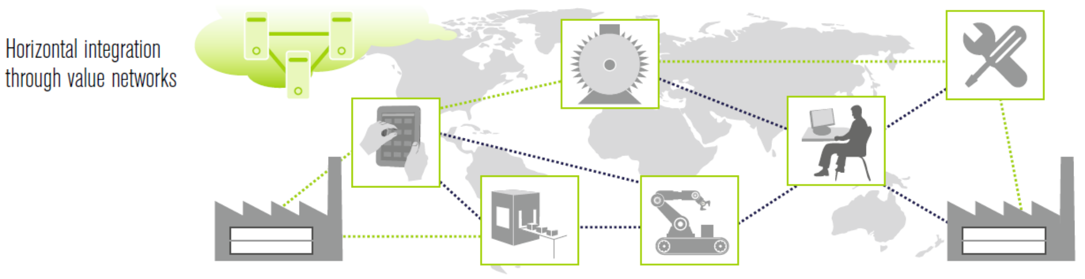

Figure 5 : Horizontal integration through value networks (Kagermann H. et al., 2013, p. 31)

The connection of the formerly stand-alone solutions of machines, components and companies by usage of the internet of things enables to process a new dimension of available data ("big data") in real time. An application can be the realization of a global early warning system for potential bottlenecks in the microchip supply chain (Kaufmann, T. et al., 2014, p. 365).

Vertical integration and networked manufacturing

The vertical integration is focused on the integration of the various IT systems at different hierarchical levels within a company to build an end-to-end solution for manufacturing systems (Kagermann H. et al., 2013, p. 32). The current hierarchical levels are sensors and actuators, control systems, production management systems, manufacturing execution systems (MES) and Enterprise resource planning (ERP). The introduction of Cyber-physical systems disintegrates the pyramid of automation from a rigid and hierarchic system towards a decentralized and flexible organized CPS based automation system, where the product controls its way through the production (Bettenhausen K. et al., 2013, p. 4). The network of CPS can create flexible and reconfigurable manufacturing systems, which can change and optimize their structure from sensor level up to ERP level to adapt to the current situation on a case-by-case basis.

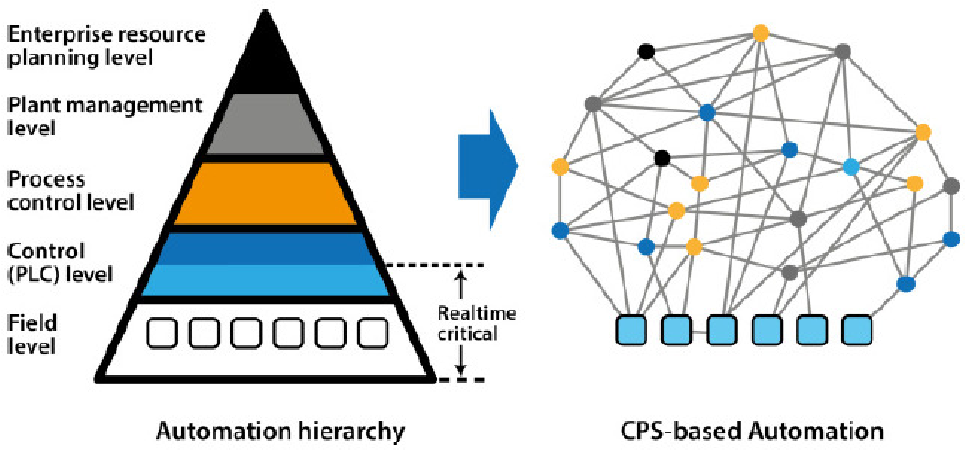

Figure 6 : Disaggregation of pyramid of Automation by CPS with decentralized services (Bettenhausen K. et al., 2013, p. 4)

End-to-end digital integration of engineering

Today the IT systems have a variety of interfaces to exchange data between different systems, which cope with the different steps in the lifecycle of a product and product manufacturing systems and limit the flexibility in the value chain from engineering to customer. The application of CPS enables do establish a model-based development, which allows the deployment of an end-to-end, modelled, digital methodology. This methodology covers every aspect from customer requirements to product architecture and manufacture of the finished product .All interdependencies can be identified and represented in an end-to-end engineering tool chain (Kagermann H. et al., 2013, p. 31). This holistic engineering approach enables to create customer-specific products for higher customer satisfaction at lower costs due to the end-to end integration of the value chain.

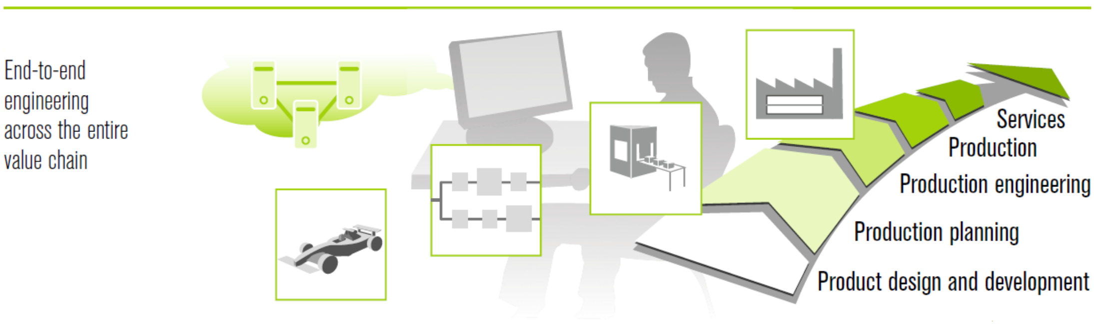

Figure 7 : End-to-end digital integration of engineering across the entire value chain (Kagermann H. et al., 2013, p. 31)

Cross-sectional technologies for Industrie 4.0

All Industrie 4.0 technologies for the digitalization of the value chain networks are characterized by the ability to build smart networks of man, machine, objects and ICT systems. The five main fields of technology are defined as follows (Bauer W. et al., 2014, p. 18) :

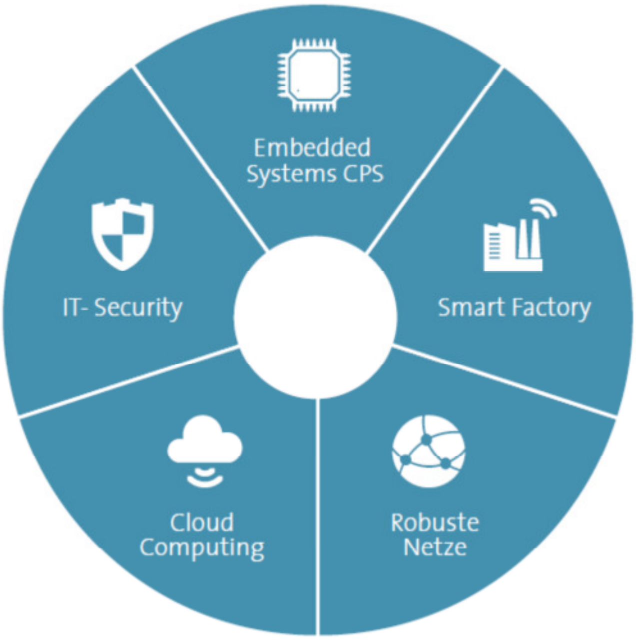

Figure 8: Groups of Industrie 4.0 technology (Bauer W. et al., 2014, p. 14)

The central element is Cyber-physical system. CPS stands for the connection of the real and the virtual world and is the result of the development and usage of embedded systems and global networks like the internet. A CPS is characterized by the ability to measure physical data with sensors and influence physical processes with actors. It can evaluate store and evaluate data and based on this data active or reactive interact with the real and the virtual world. CPS are interconnected via digital networks (local and global, wired and wireless) and can use worldwide available data and services. Cyber-physical systems own a multimodal Man-to-Machine interface for communication and control. CPS act location independent, partly autonomous, partly automatized, context aware, multifunctional, connected and distributed for their stakeholders and users (Geisberger E. et al., 2012, p. 22) .

Based on the state of the art knowledge, seven groups of technology have been identified that are necessary for realization of the CPS capabilities (Geisberger E. et al., 2012, pp. 127-128) :

- Physical recognition of situation (Physical awareness, X-Awareness)
- Planning and anticipatory, partly or fully autonomous action
- Cooperation and negotiation between cyber-physical systems
- Man-machine interaction
- Learning (Data mining learning of machine)
- Strategies of self-organization and adaption
- Base technologies

A lot of the necessary technologies still have to be developed or improved, based on the current state. Exemplarily mentioned: Sensor fusion, pattern recognition, artificial intelligence, multi agents systems, intention recognition, human awareness, data mining and ad hoc networks.

Cyber-physical production systems (CPPS)

The application of CPS technology in production creates a cyber-physical-production-system (CPPS) that will e.g. optimize the process flow and schedule decentralized and in real-time. The CPPS builds a Smart factory, that is flexible to fulfill individual customer requirements and can react in real time at the occurrence of unexpected disruptions. The CPS technology is the enabler for the next step of decentralization in manufacturing. The real world of manufacturing will have a real time model in the virtual world, where changes in the real world will be updated in real time. The possibility of the real time reaction will improve e.g. the logistic targets of the production.

2.2 Production Planning and Control (PPC)

The logistic target of production is the fulfilment of customer orders in the right time, the right amount, at the right place, for the right price with the right people. As shown in Chapter 1, the target system of production planning and control describes the stress field of optimization of production to satisfy customer requirements in the most efficient and effective way. The four contradictory targets of the logistic target system are short lead time, high adherence to schedule, low inventory and high utilization, where short lead time and high adherence to schedule represent the logistic performance and low inventory and high utilization the logistic cost. The instrument to optimize the positioning of production in this stress field is production planning and control (PPC), which is in the center of in-company managerial activities (Arnold D. et al., 2008, p. 324).

2.2.1 Terms and principles

In general, the main steps of production planning are master production scheduling, Material requirements planning and capacity requirements planning. These steps are executed in a long- to midterm timeframe.

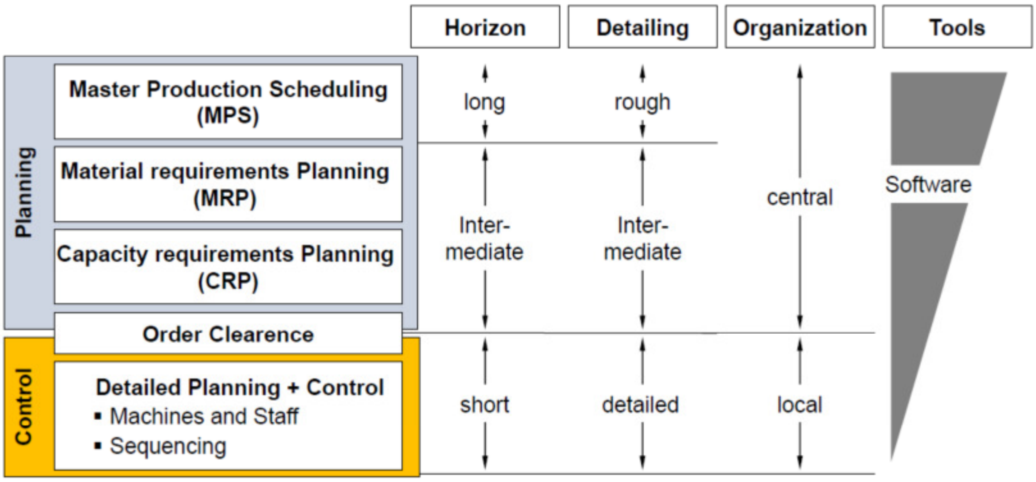

Figure 9 : Characteristics of the Planning Process (Löllmann P., 2013, p. 8)

Based on customer orders and forecasts from national sales organizations the production planning and control activities start from the long term perspective with master production scheduling (MPS). The MPS disaggregates the aggregate production plan and specifies which specific product has to be produced in which quantity and timeframe.

In the midterm step of material requirements planning (MRP) the dependent demand is determined, which creates production orders and procurement orders for the purchasing department for the net requirements, based on a Bill of Material (BOM), accurate inventory records, outstanding purchase orders and required lead times. In the third step of production planning, the capacity requirements planning (CRP), the capacity requirements are compared with the available resources. Depending on the needs, the capacity can be accommodated by increase of capacities (e.g. overtime) or by adjustment of the capacities, e.g. by usage of contract manufacturers or shifting to a time of lower capacity utilization (Heizer J et. al., 2011, pp. 578 -580).

Short-term scheduling (=Short-term Production Control) deals with the detailed planning, control and timing of operations and translates capacity decisions, aggregate planning and master schedules into job sequences and specific assignments of personnel, materials and machinery (Heizer J et. al., 2011, p. 616). Short term scheduling is the operative part of production planning and control (PPC), where the demand is allocated and prioritized in dependence of the managerial emphasis of the target system of production planning and control. According to Lödding's model of Production Control, the four tasks of Production control are Order generation, Order release, Order sequencing and Capacity control (Lödding H., 2008, p. 7) and are part of PPC.

The Automotive Industry pursues due to the lean philosophy of their production systems a mixed form of built-to-order/assemble-to-order (BTO) strategies and build-to-forecast strategies (BTF) (Holweg M. et al., 2004, pp. 4-6), where the customer decoupling point is allocated in front of the assembly line.

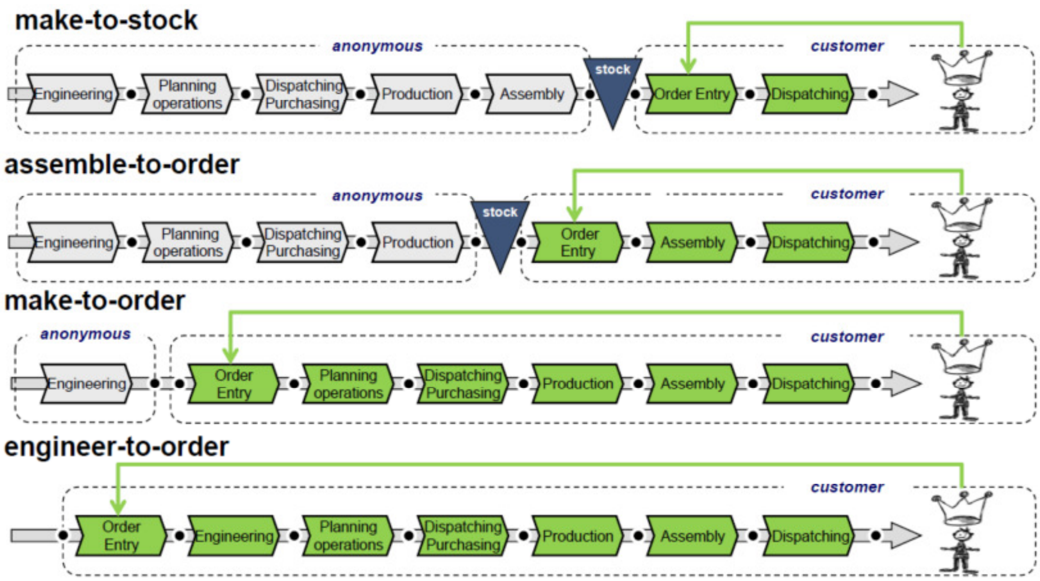

Figure 10 : Order Management and Process Strategies (Löllmann P., 2013, p. 5)

The car is built in the vehicle assembly plant based on a customer order, but the components and modules (including the powertrain aggregates) are normally built non-order-related, based on a prognosis. If the scheduling of the powertrain units is integrated into a pearl chain concept of the vehicle plant, the aggregates (engine and transmission) can be assembled and delivered in Just in Sequence (JIS) due to the frozen period of a pearl-chain-concept within approximately four days range to the vehicle assembly plant (Klug F., 2010, p. 376).

2.2.2 Classification in Aachen PPC Model

The Aachen PPC model was designed for the simplified characterization of the relevant relationships in PPC. The Aachen PPC Model describes the different sub-aspects of PPC and supports the determination of targets and optimization of PPC systems. The main task of the Aachen PPC model is the description of parts of PPC from different points of view, which are covering different structures and formulations optimized for the intended purpose. The four reference perspectives are: the task view, the process architecture view, the functions view and the process view (Schuh G. et al., 2012, p. 18).The task view perspective is divided into the groups of network tasks, core tasks, cross-sectional task and an underlying, the three tasks supporting data management. (Schuh G. et al., 2012, p. 30)

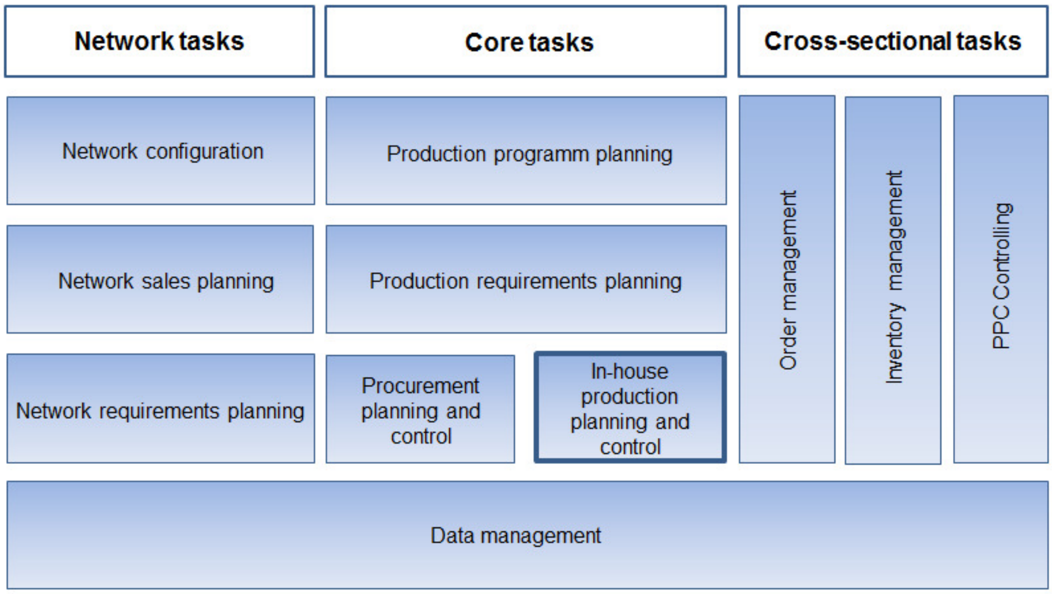

Figure 11 : Task view of Aachen PPC model (Schuh G. et al., 2012, p. 30)

The Aachen PPC model generally defines the sub tasks of in-house production planning and control as lot sizing, fine scheduling, detailed resource planning, sequence-planning, disposability planning and order enabling (Schuh G. et al., 2012, p. 31). The discussed tasks of master program scheduling, sequencing and re-sequencing are part of the general sub-tasks of in-house production planning and control. Therefore the tasks of master program scheduling, sequencing and re-sequencing can be classified as tasks of in-house production planning and control core tasks within the Aachen PPC model.

2.2.3 Principles of control in PPC

This this chapter introduces into the control principles of PPC and highlights the advantages and disadvantages of different types of control. At the end a conclusion is given concerning the possible advantages concerning powertrain manufacturing with an assembly line and upstream component lines.

Decentralized control

Decentralization can be defined as "Transfer of decision making power and assignment of accountability and responsibility for results. It is accompanied by delegation of commensurate authority to individuals or units at all levels of an organization even those far removed from headquarters or other centers of power" (Murcko T., 2014). Decentralized control in terms of PPC means, that processes can be designed decentralized and especially planning decisions can be determined faster. Decentralization creates a higher flexibility for organizational units in terms of PPC through smaller decision structures and lower effort of coordination within the decentralized unit. From the overall business perspective, a decentralized organization can result in a higher effort of coordination of PPC for the superior units (Schuh G. et al., 2012, pp. 301-302). Target is the creation of independent organizational units that can respond faster at changing customer- and market demands. In decentralized PPC the planning and control is executed within the concerned stage of production. The stage of production *n* plans the production schedule on its own responsibility. The planning of the downstream production stage *n+1* hands over the material requirements derived by the orders to the upstream production stages (Dangelmaier W. , 2009, p. 1338). One implementation of decentralized PPC is well known as the Pull principle which establishes a direct customer-supplier-relationship, where the necessary material is "pulled" from the production stage *n* directly to the production stage *n+1* in the right amount and the right time.

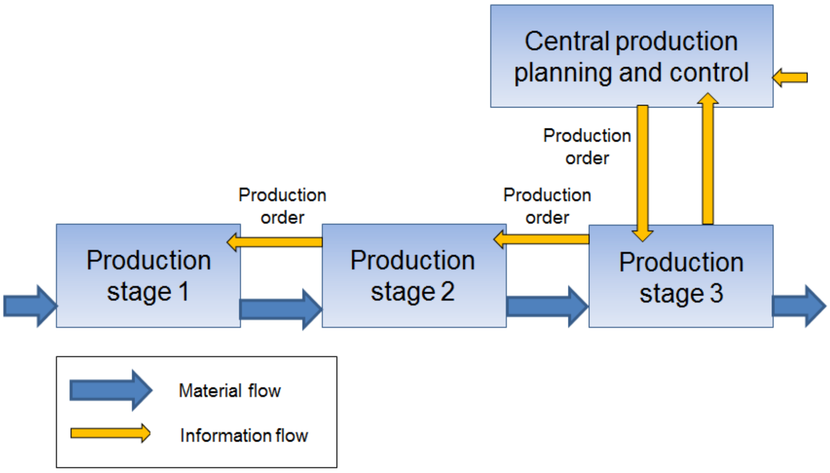

Figure 12 : Design of Pull Principle (based on FML TU München, 2014)

Examples of possible decentralized control principles are according to (Kletti J., 2006, pp. 14-15) :

- **KANBAN:** Signal to the producing area gets a signal from the consuming are about the needed amount of material and timeframe for delivery. This system can be realized with cards and is used where continuous flow (one piece flow) is not practical. The system was developed by Toyota (Liker J., 2004, p. 108).

- **CONWIP** Method (Constant work in progress): based on the KANBAN system but the control loop consists of more stations of the flow production

- **One piece flow** (synchronous production): an ideal manufacturing line with interlinked work stages produces in customer tact. Therefore only one stage in the whole value chain has to be controlled. The pacemaker process step is the process step controlled by the customer order.

- **Agent systems:** superior ICT systems determine basic dates based on delivery dates. Based on these specifications, the orders, material, work pieces, work systems machines and transport systems negotiate the work flow decentralized and autonomous, regarding the actual state of production. For a detailed description of autonomous control see chapter 2.2.2.2.

Decentralized control in terms of autonomous control

Beside of the classical approach of decentralized control, where the level of decision making is delegated to the organizational units on the shop floor, a new approach of decentralized control is under research. This new approach is the autonomous control of logistic objects in dynamic logistic systems. Autonomous control is seen, especially in the context of Industrie 4.0, as one option to handle the increasing complexity and dynamics of logistic systems. Autonomous control is defined by Windt and Hülsmann as "*processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions independently. The objective of Autonomous Control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity*". (Hülsmann M. and Windt K., 2007, p. 8) From this global definition, a focused definition for the main tasks of logistic objects in autonomous controlled logistic systems can be derived: "*Autonomous control in logistics systems is characterized by the ability of logistic objects to process information, to render and to execute decisions on their own."* (Windt K. et al., 2008a, p. 573). In the context of autonomous control, the logistic objects are defined in a broader sense than in classical logistics. They are defined as products, orders, production facilities, machines, transport systems and tools.

Centralized control

The traditional PPC approach is characterized by a centralized organization where the schedule of orders is planned at one central location and sent to the different production departments for execution. Central PPC is a Push-Principle, where the orders are "pushed" through the manufacturing area. Normally this process is supported by IT systems, e.g. ERP systems. (Hachtel G. & Holzbaur U., 2010, p. 114).

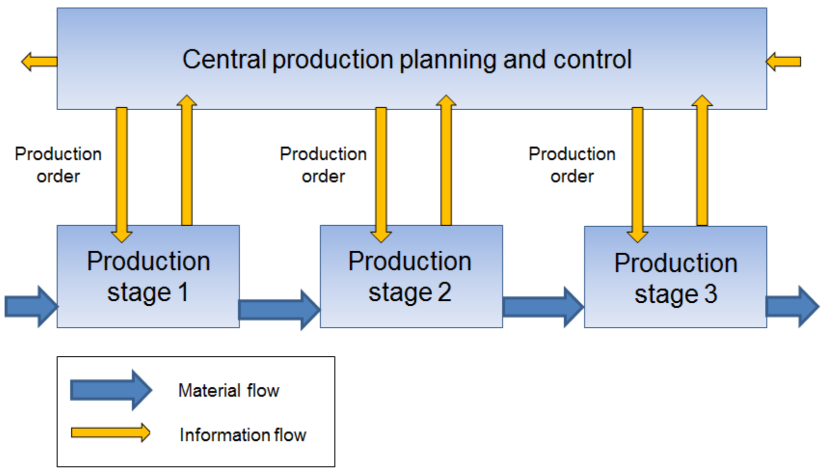

Figure 13 : Design of Push Principle (based on FML TU München, 2014)

The appropriate type of production control system for push-systems is highly dependent on the structure of Manufacturing, like job shop production, cellular manufacturing and continuous flow production (Kletti J., 2006, pp. 13-14) :

- **MRPII (Material Resource Planning):** an extension of MRP (Material requirements planning) system by capacities of human resources and machines (job shop production), part of an ERP System

- **Concept of cumulative quantity** (germ.: Fortschrittszahlenkonzept), mainly used in Automotive Industry

- **„Belastungsorientierte Auftragsfreigabe“ (BOA)**

Today companies implement Manufacturing Execution systems, because ERP systems normally do not allow immediate predications about the real production procedures. ERP systems are supported by MES, which “offer a meaningful functional addition to plan and control direct all manufacturing processes, to ensure process transparency, and to map currently the flow of material and information within the supply chain.” (VDI e.V., 2007, p. 2). In other words, MES is the management layer between the ERP system and manufacturing level and copes with the detailed scheduling & process control, Resource management and material management.

Decentralized vs. centralized control

Both control principles have advantages and disadvantages, which have to be assessed according to the related case of application, and can be applied in different combinations at different levels of production stages.

Advantages of decentralized control (Hachtel G. & Holzbaur U., 2010, p. 114)**:**

- Reduced effort for planning and control
- direct synchronization with actual demand
- better control of inventory
- less information necessary
- Integration of the executing level (foreman an workers on shop floor) into planning leads to usage of knowhow at shop floor level and identification with production schedule (Spath D. et al., 2013, p. 96)
- Reduction of complexity and increase in flexibility

Disadvantages of decentralized control:

- Problems of coordination for complex structures of material flow
- Poor adaptability against variations in customer demand

Advantages of centralized control:

- Adaptability of all material flows towards predictable variations of customer demand
- Complete coordination of material flow in whole supply chain to minimize costs (logistic-, production- and inventory- cost)

Disadvantages of centralized control:

- High effort of planning and information exchange between involved departments in case of changing demands
- Communication problems between the involved departments
- Low acceptance of production schedule at shop floor level
- Production data acquisition necessary needed for transparency and feedback
- Too little freedom of action on the operative level (Löllmann P., 2013, p. 15)

In summary, the added value of "classical" decentralization is the opportunity to reduce complexity in PPC and assignment of responsibility to the shop-floor level. The fulfillment of the logistic objectives of the short-term scheduling and production sequencing tasks can be supported by decentralization through the segmentation of the planning complexity. The introduction of cyber-physical systems, that enable logistic objects like orders, parts and equipment to render to a certain extend decisions on their own, could be an enabler for the improvement of the tasks of short-term scheduling and sequencing of automotive powertrain plants by further segmentation of the planning complexity.

2.2.4 Limits of decentralized control in terms of autonomous control

Decentralized control and especially decentralized control specified as autonomous control promises to be an attractive approach to handle complexity and dynamics in logistic systems by increasing flexibility and robustness to achieve the logistical objectives. But it also expected that autonomous control of autonomous logistic systems can negatively impact productivity, e.g. by the immanent redundancy of resources and structures and the delegation of decision power. (Hülsmann M. and Windt K., 2007). The area of conflict of an autonomous logistic system can be characterized by three parameters: the degree of autonomous control, the degree of product system complexity, and the degree of logistic objective achievement.

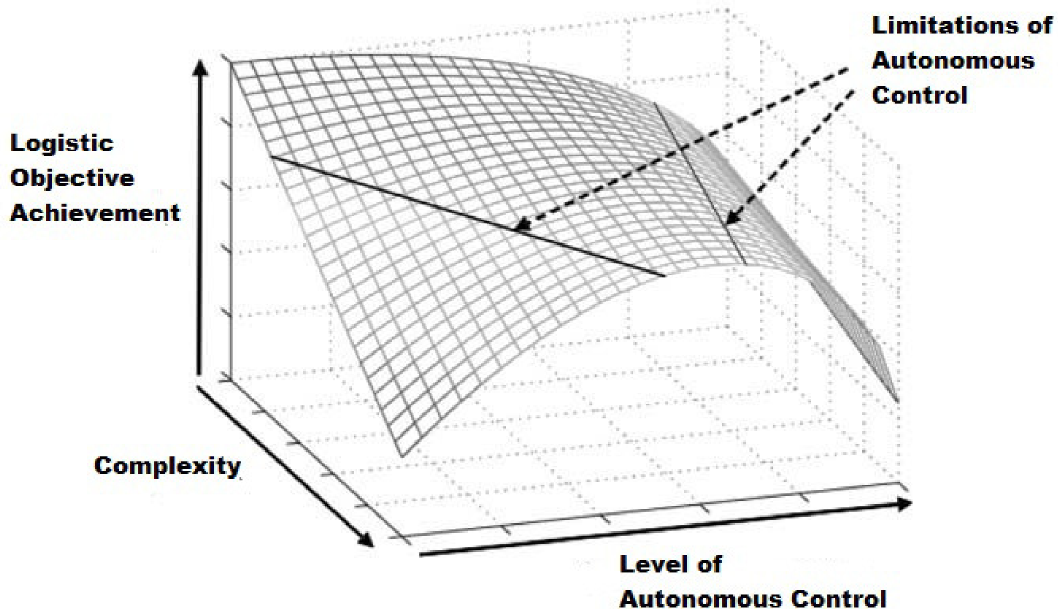

Figure 14 : Application potentials and limitations of autonomous control (Windt K., 2008, p. 355)

The curve shape is defined based on the following assumptions (Scholz-Reiter B. et al., 2007, p. 181) :

- The more complex the logistic system is, the lower the logistic objective achievement
- Logistic systems with lower complexity and low degree of autonomous control have an higher logistic objective achievement than with an high degree of autonomous control
- The optimum of autonomous control does not correspond to the maximum of autonomous control. For a given high level of complexity, the logistic objective achievement rises with increasing level of autonomous control, reaches an optimum and then declines.

In my opinion this method shows very clear that the necessary level of decentralization respectively autonomous control is depending on the boundary conditions of logistic objectives and complexity of the considered planning and control task. For the definition of a target concept of short-term scheduling and sequencing in terms of Industrie 4.0 the limitations of autonomous control for a lean production system based on continuous flow will be considered.

2.2.5 Methods of evaluation of the degree of decentralized control

The literature study for evaluation methods of the degree of decentralized control found only one method that seemed to applicable for the given problem. The method was developed for the evaluation of the level of autonomous control of logistic systems. The authors Böse and Windt state that the catalogue of criteria "*was defined with a very high degree of abstraction to enable a universal application in different fields of logistics*" (Böse F. and Windt K., 2007). Therefore it seems to be appropriate to use this method for the evaluation of the degree of selected tasks of PPC in Chapter 4. The method will be outlined in a detailed way, as the method is giving a good overview about the features of decentralized, respectively autonomous control.

The Cooperative Research Centre 637 "Autonomous Cooperative Logistic Processes – A Paradigm shift and its Limitations" at the University of Bremen is since 2004 researching in the field of autonomous controlled logistic systems. Within the scope of this research project an evaluation system for level of autonomous control was developed. Based on the definition of the main characteristics of autonomous control given in Chapter 2.2.2.2, that logistic objects can process information and render and execute decisions, the different system layers of autonomous control are defined as decision making layer, information processing layer and decision execution layer. The decision layer is characterized by the decision making ability, which includes the planning and control tasks and enables logistic objects to assign their progression. The decision making process implies the identification and evaluation of decision making alternatives based on a decentralized objective system and the selection and execution of the best rated alternative. The decision making is based on the information processing ability. Logistic objects in autonomous controlled manufacturing systems must have the possibility to interact with their environment and to process and store data. The execution layer is defined by the ability to execute the decisions of the logistic object. The logistic object has to be flexible to react at unforeseen influences (Böse F. and Windt K., 2007).

Normally logistic systems will not be fully autonomous due to the fact that logistic systems can probably include conventionally managed and autonomous controlled elements and sub-systems, or elements will only have a low level of information processing ability. Based on the necessity to characterize and measure the logistic systems, a catalogue of criteria was defined for the system layers of autonomous control. To make the catalogue of criteria applicable to define the level of autonomous control, the criteria were operationalized. Since the different criteria have different influence on the degree of autonomous control, the criteria themselves are weighted by pairwise comparison. The properties of the criteria are weighted from "0" absolutely conventionally controlled to "3" absolutely autonomously controlled. The sum of the products of the single rating of the property and the weighting of the criteria derives an indication of the level of autonomous control in the analyzed logistic system (Böse F. and Windt K., 2007).

The properties of the thirteen criteria of autonomous control are described as:

Decision-making criteria (Böse F. and Windt K., 2007)

- The time behavior of the objective system describes the adaptability of the local logistic objective system in case of disturbances. (Windt K. et al., 2008a)
- The organizational structure describes the level of independence between single elements and a central logistic coordination entity (Hülsmann M. and Windt K., 2007).

- The number of decision alternatives describes the scope of action for decision alternatives of the logistic object.
- The type of decision making describes the basic type of algorithm, with is underlying the decision making process
- The criterion of the location of decision making describes the layer of the logistic system on which the decision is made
- The system behavior describes the predictability of the system and system element behavior. "*Non-determinism means, that despite of the precise measurement of the system status and knowledge on all influencing variables of the system, no forecast of the system status can be made*"

Information processing criteria

- The location of the data storage describes where the data is processed
- The location of the data processing describes where the data is processed
- The Interaction ability describes the level of ability of the logistic object to interact with the other elements in the system, from not existing abilities to coordination abilities, e.g. to coordination of a complete lot of parts

Decision execution criteria

- The resource flexibility describes the ability of a resource to adjust to changing requirements, e.g. to handle different parts
- The identification ability describes the possibility to identify the logistic object within the system
- The measuring ability defines the ability of the logistic object to measure its current state e.g. via sensors
- The criterion of mobility describes the possibility for the logistic object to move through the system with the help of other elements or on its own

Criteria category C_i	Criteria C_{ij}	Weighting G_{ij}	Properties P_{ij}			
Decision-making criteria	Time behaviour of objective system	9	static 0	mostly static 1	mostly dynamic 2	dynamic 3
	Organisational structure	12	hierarchical 0	mostly hierarchical 1	mostly heterarchical 2	heterarchical 3
	Number of decision alternatives	12	none 0	some 1	many 2	unlimited 3
	Type of decision making	8	static 0	rule-based 1,5		learning 3
	Location of decision making	15	system layer 0	subsystem layer 1,5		system-element layer 3
	System behaviour	11	elements and system deterministic 0	elements non-/ system deterministic 1	system non-/ elements deterministic 2	elements and system non-deterministic 3
Information processing criteria	Location of data storage	1	central 0	mostly central 1	mostly decentralised 2	decentralised 3
	Location of data processing	6	central 0	mostly central 1	mostly decentralised 2	decentralised 3
	Interaction ability	14	none 0	data allocation 1	communi-cation 2	coordination 3
Decision execution criteria	Resource flexibility	2	inflexible 0	less flexible 1	flexible 2	highly flexible 3
	Identification ability	4	no elements identifiable 0	some elem. identifiable 1	many elem. identifiable 2	all elements identifiable 3
	Measuring ability	6	none 0	others 1	self 2	self and others 3
	Mobility	1	immobile 0	less mobile 1	mobile 2	highly mobile 3

Level of autonomous control

$$\sum_{i=0}^{n} \sum_{j=0}^{n} G_{ij} * p_{ij} = 220$$

C_i = Criteria category
C_{ij} = Criterion
G_{ij} = Weighting of criterion
P_{ij} = Property of criterion
p_{ij} = Fulfilment of criterion

increasing level of autonomous control →

Figure 15 : Catalogue of criteria of autonomous control (Böse F. and Windt K., 2007, p. 68)

Based on the weighing of the criteria in this catalogue of criteria of decentralized control, the Top five criteria are localized on the decision making system layer, in particular the location of decision making, the organizational structure, the number of decision alternatives and the system behavior. From point of view of the information processing layer, the interaction ability of the logistic objects is the most important criteria, see figure 14.

The evaluation method of Böse and Windt seems applicable to investigate the level of short term scheduling and sequencing due to the high abstraction level of the catalogue of criteria. Some of the criteria might have some room for interpretation during evaluation but of the overall result might give indication of the degree of decentralization. The result will show the opportunities concerning the increase of autonomy of the particular property. The reasonableness of the potentials has then to be combined to an overall picture and expected added value in terms of decentralized control of Industrie 4.0.

2.3 PPC in the context of Industrie 4.0

Nowadays companies are faced with a high competitive, fast changing market and have to keep their competitive advantage by designing and producing the right products in a high number of variants in always shorter timeframes. While complexity of products and processes and the volatility of the markets are rising, the customers expect a high ability of supply and on-time delivery. The increasing importance of the factor time leads to short term changes in the schedules of PPC. Based on the survey of Fraunhofer, 62% auf the companies have a high or very high effort of short term production planning and control. As the main reason for the high effort in PPC the respondents name the minor quality and the lack of actuality of production data (Spath D. et al., 2013, pp. 91,93). The real-time availability of data and the decentralized decision-making abilities of cyber-physical production systems have the possibility to initiate new chances and opportunities for the improvement of short-term PPC.

2.3.1 Chances and opportunities

The vison of Industrie 4.0 promotes the Introduction of cyber-physical systems, which promise an added value concerning production planning and control. The real time availability of information and the higher density of information of a CPPS bring a higher level of transparency into production. The transparency enables the production to be controlled decentralized. The decentralized PPC pursues a local optimization of orders and order sequence over a limited subject area, in opposition to a conventional centralized and deterministic planning. Therefore decentralized PPC can better incorporate specific boundary conditions into its optimization process and act more flexible in case of changing requirements. Another important aspect of decentralized PPC is the integration of the executing level, because the knowledge of foreman and workers of the shop floor has to be integrated into planning (Spath D. et al., 2013, pp. 96-97). Although decentralized control reduces the complexity, a production system is expected to need a central system that delivers data for the decentralized systems.

The following chapter will give an idea about PPC in terms of Industrie 4.0 like the opportunity of cyber-physical production management, lean manufacturing in context with Industrie 4.0, and an outlook of implementation examples.

2.3.2 Cyber-Physical Production Management

Current IT systems as Advanced planning systems often do not predict the future state of the production planning reliability. One of the main reasons of the deviation between the planning and the production reality is the adaption of the real production system in the IT system. One of the reasons is that the initial implemented model drifts s apart from the production reality, due new process, machines or variants of products, which have not been integrated into the actual model in the IT system. As part of the research project "ProSense", an approach of cyber-physical production management was presented, which determines the deviations between the planned schedule and the production process reality. Based on the identified deviations and their causes, the PPC can be adjusted towards a dependable high resolution PPC. The ability of CPS of sensing data, computing data and sending them to a network, is used to collect all necessary information from processes, machines and products to build an initial data basis for optimization of the IT simulation tool. Based on former planning information and the information of CPS, a judgment tool compares the Information of ERP systems, MES systems planning and the shop floor reality and determines the deviations and their causes. With this information a simulation tool optimizes the model in the IT system to improve the reliability of the model to improve the prediction quality of the forecast model of the PPC tool. (Schuh G. et al., 2013, p. 479). The main Contribution of CPS is the high resolution data collection, which is crucial for the depiction of the shopfloor reality as essential information for the improvement of the IT systems of PPC.

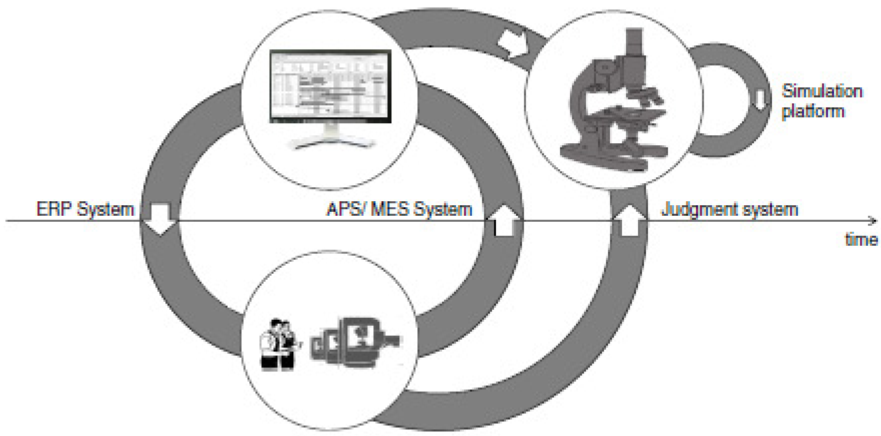

Figure 16 : Approach of cyber-physical production control (Schuh G. et al., 2013, p. 480)

2.3.3 Lean Production

Lean production is based on the elimination of any type of waste in the production process, like overproduction, excess inventory, waiting, unnecessary movement, unnecessary transport, defects, over processing and unused employee creativity. A Lean Production system orients all activities towards the customer. It produces according to the customer demand and at the right time. Inventory is reduced to an absolute minimum and the production resources are optimized for short lead time. The products are produced in customer tact according to the customer demand in a continuous process flow (one piece flow) and a leveled production schedule. A lean production is characterized by decentralized customer oriented structures and by pull system techniques, which increase the throughput of the production system (Liker J., 2004).

All in all, the lean production with minimum inventory and short lead time reacts as well "in real time" according to the customer demand like the Industrie 4.0 vision. It is a decentralized planning and control principle, which is based on standardization and predefined processes, while the Industrie 4.0 focuses on ICT and the idea of intelligent logistic objects, which optimize and bargain their flow through production. But lean production and Industrie 4.0 are not contradictory. Industrie 4.0 will further optimize the lean production concerning real-time availability of data and services. The smart factory with Industrie 4.0 technologies will be based on the lean production principles (Bauernhansl T., 2014, p. 19).

2.3.4 Implementation example MES

A manufacturing execution system is defined as an integrated IT-solution which supports the control of the manufacturing process. It connects the ERP system and the manufacturing execution layer (vertical integration), horizontally the MES covers the complete production process (horizontal integration). According to VDI 5600 an MES should fulfill the eight main tasks of detailed scheduling and production control, equipment management, material management, personnel management, data acquisition, performance analysis, quality management and information management. From the point of time behavior, MES is a real time system, which is directly coupled to the subordinate system layer for permanent data acquisition of the actual state of production (VDI e.V., 2007). MES evaluates the current state of production and evaluates deviations to the schedule. The system presents the worker comprehensive information in real time for their decision process of process optimization.

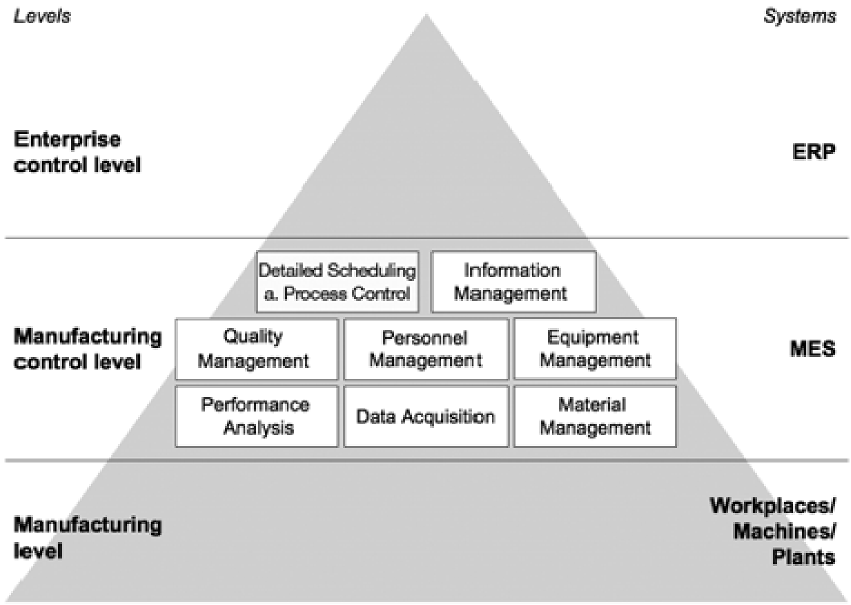

Figure 17 : Classification of MES into the management levels of an enterprise (VDI e.V., 2007, p. 7)

The MES task of detailed scheduling and production control fulfills the purpose of schedule generation and development of conflict resolutions. The schedule generation can be started by an ERP run or unexpected event. The MES system has to solve conflicts e.g. concerning resource capacity, material availability and constrains concerning order deadlines. The application of MES is expected to improve the production process in regard to reduction of lead time, increased readiness for delivery, decrease of setup effort, increase of throughput and decrease of stocks and WIP. Concerning the planning efforts, a decrease in operation planning and operational coordination efforts is expected. The application of MES brings a high level of transparency into the production process. According to Kletti, MES are a first step into the direction of Industrie 4.0. MES are an important basis and even a driver of Industrie 4.0 as a central instance of real time communication and data availability and a source of information for decentralized planning and control. It is expected, that MES will provide the global data basis for autonomous acting CPS, which will increase communication efficiency and therefore improve the efficiency of the overall system. In the Framework of Industrie 4.0 MES systems will efficiently support decentralized manufacturing systems and will assure, that the people on the shop floor keep the overview over the autonomous systems and the superior decision-making ability (Kletti J. et al., 2013).

2.3.5 Implementation example PLM

A main element of Industrie 4.0 is the integration of ICT systems into the manufacturing area and an improvement of the quality of production planning and control. This vision implies the seamless availability of information of the product from beginning to the end of the lifecycle. The Product Lifecycle Management is an information strategy that builds a coherent data structure by consolidating systems. Today the PLM software allows companies to manage the entire lifecycle of a product efficiently and cost-effectively, from ideation, design and manufacture, through service and disposal. PLM can be seen as a comprehensive approach to innovation built on enterprise-wide access to a common repository of product information and processes (Siemens , 2014). Today PLM systems are more focused on the management of design and product data, while the linkage to production planning and control has to be improved. For the vision Industrie 4.0 it is essential to improve the consistency of data and to have a unique source of information, the so called "single source of truth" e.g. for production planning and control. This requirement can be fulfilled by data transfer from the PLM system to the PPS system (Schuh G. et al., 2014b, p. 284).

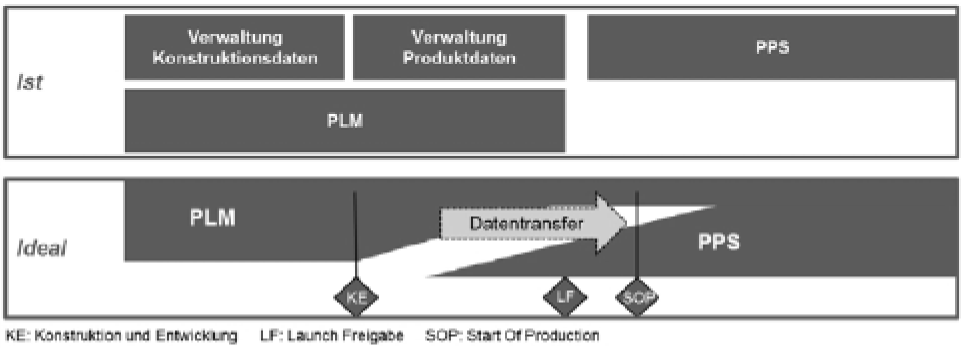

Figure 18 : Ideal state of PLM in terms of PPS (Schuh G. et al., 2014b, p. 283)

2.3.6 Earlier concepts of decentralized control – risks and challenges

In the history of PPC many concepts concerning decentralized and autonomous control can be found. The most well-known concepts are the "fraktale Fabrik" and the "Holonic Manufacturing System" (HMS). The concept "fraktale Fabrik" implements autonomous self-control on management level. The "fraktale Fabrik" is defined as an open system, which consists of autonomously acting fractals (=units), which have a self-similar target system. These fractals build through their dynamic structures a vital organism. The "fraktale Fabrik" is, as a consequence, an adaptive system which can permanently adapt to changing requirements because of the ability of autonomous control and self-optimization (Warnecke, H.-J., 1993). Precondition for autonomous control of the fractals within the overall system are relatively autonomous, stable sub-systems. The autonomous control of the subsystems leads to a kind of self-organization of the entire system.

The holonic manufacturing system is an example for the self-organization of production systems. The HMS consists of autonomous, cooperating and intelligent modules, the so called “holons”. Holons have the ability to adapt and to configure by themselves. They represent real components of the system like resources and products, and also virtual components like orders. The holons cooperate and interact with other holons, and they can react autonomously in case of unforeseen circumstances without contacting a superior control system. The social skills of communication, negotiation and cooperation result in autonomous controlled processes within the production system. A system of holons builds the holarchy that can co-operate to achieve a goal or objective. The holarchy defines the basic rules for co-operation of the holons and thereby limits their autonomy. The holonic concept integrates the human into his concept as an elementary part of the system (Van Brussel, H. et al., 1998, p. 256).

These approaches are transferable to the organizational structure of production systems. Within these approaches decisions are taken based on current data from production. Since these highly decentralized approaches prevent a prediction of their future behavior, they react quickly to current events but are not planning prospectively (Schuh G. et al., 2014a, p. 470).

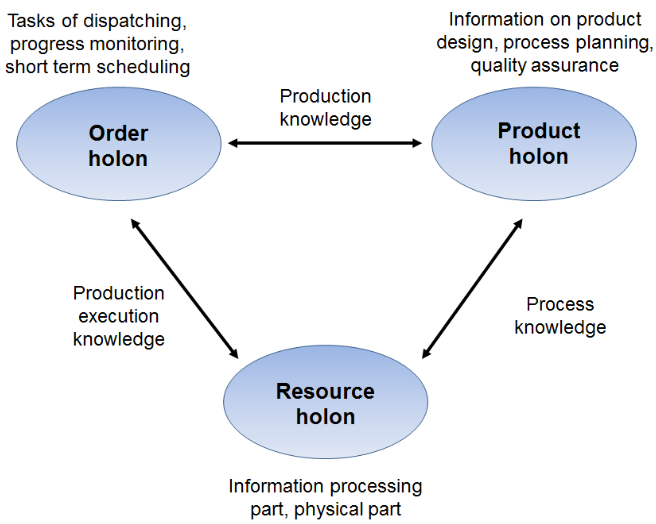

Figure 19 : Reference architecture for Holonic manufacturing systems (Scholz-Reiter B. & Freitag M., 2007)

The concepts of the Holonic manufacturing system and “die fraktale Fabrik” reveal that the concept of decentralization of control is not a new aspect. Decentralization is a constantly recurring aspect of operations research and a complete new feature that has emerged with Industrie 4.0. The second core feature of Industrie 4.0, the integration of ICT into the manufacturing process, is as well not a new trend. According to Jasperneite, the integration of intelligent technical systems into Automation is subject of discussion since many years. To mention only the catchwords since the last fifteen years: Internet of things, Ambient intelligence, Cyber-physical systems, Factories of the future, Manufacturing 2.0 and Industrie 4.0. From his point of view many aspects of the integration of ICT into the Automation of manufacturing are already standard to a certain extent. The main fields of action are seen in the field of the Self-X abilities: the self–optimization, the self-configuration and the self-diagnosis (Jasperneite J., 2012).

The development of Industrie 4.0 from a vision to an implemented technology contains risks and challenges. As the concepts of holonic manufacturing and “fraktale fabrik” did not become a widespread standard, the decentralization in terms of Industrie 4.0 and the Industrie 4.0 itself has to prove the added value under industrial conditions.

2.4 Conclusion

In his chapter the theoretical foundations of Industrie 4.0, the principles of Production planning and control including the aspect of decentralized control were discussed. An outlook on the opportunities of PPC in context of Industrie 4.0 was given. An approach for the evaluation of the degree of autonomous control was presented in detail, which will be used for the analysis of the degree of decentralization of an automotive powertrain production.

The vision of Industrie 4.0 shows manifold opportunities concerning the implementation of cyber-physical systems. The real time availability of data and the possibility of decentralized decision-making in cyber-physical production systems promise new possibilities for manufacturing as a whole, and specific for the production planning and control. Necessary technologies have still to be developed.

“Classic” decentralized control principles of PPC, like the pull principle based on the Toyota production system, have already proven their benefits.

3 Production Planning and Control of an automotive powertrain plant

The vision of Industrie 4.0 and the corresponding decentralization of decision making in literature is seen to be a very promising approach for the generation of an added value in manufacturing. To investigate the potentials of decentralization in terms of Industrie 4.0 for production planning and control, the tasks of short-term scheduling and sequencing for an automotive powertrain assembly plant are considered. Chapter 3 is dealing with a theoretical use case of the planning processes, while Chapter 4 describes and analyses a case of application.

The research will focus on the short term production planning and control of assembly lines and the upstream manufacturing areas. The in- and outbound supply chain including material disposition will be considered as variable of disturbance, but will not be taken in account for an Industrie 4.0 scenario. As an introduction a short overview about the main production steps of engine and transmission manufacturing are presented and the characteristics of a flow production will be discussed. Afterwards the Production planning and control tasks in an automotive powertrain plant will be discussed theoretically. The structure will refer to the PPC of automotive vehicle plants, because of the similar production management systems of vehicle and powertrain assembly plants. For tasks that are not applicable under today's boundary conditions, or differ between powertrain and vehicle assembly plants, comments will be made. Most of the literature only refers to the PPC of final assembly lines. In this chapter the decentralized PPC of the upstream machining areas will be also be taken under consideration. The word powertrain is defined in this context as engine or transmission.

3.1 Opel Wien GmbH: Products and customers

The research for this master thesis is based the PPC structure of the Opel powertrain plant in Vienna, Austria. The plant was founded in 1983 and is since then part of the global General Motors automotive network. The plant produces at three manufacturing areas three different product families, which consist of an engine family, a 5-speed transmission family and 6-speed transmission family. Each product family comprises of minimum sixty and up to over eighty individual variants, based on engine or transmission assembly number. On a daily basis more than 6000 aggregates are shipped to customers worldwide. The customers for a powertrain plant are from a volume perspective mainly vehicle assembly plants. A low portion of orders is placed by the aftersales organization and by product engineering for development activities. The majority of the engines and transmissions are shipped to vehicle assembly plants of the Opel Group in Spain, United Kingdom, Germany, Poland and Russia. Depending on the product family between ten and thirty percent are shipped overseas to GM or GM-Joint venture plants in the USA, Korea, China, Australia and Brazil. The supplier base of a powertrain plant is as globalized as the customer base. Today the purchased goods are delivered not only from Europe, but also from as an example China, India, Brazil, Japan, South Africa and the USA (internal source)

3.2 Production process steps of powertrain manufacturing

An internal combustion engine is an assembly product that is composed by a variety of parts, modules and in house machined components. The production process of an engine can be mainly categorized in two basic steps: The machining of the in-house machined parts and the assembly at the assembly line. The production process starts with the machining of main components of the engine on highly automatized transfer lines or linked machining centers. The work systems build a flow production line for mass production. The different work systems in the production lines are working according to a leveled cycle time to create continuous flow. The machining lines are flexible to produce different variants of the basic design of the product, it can be necessary to consider possible setup times and cost when changing from one variant to another. The machining areas and the assembly line are decoupled by buffers. These buffers can be used to absorb breakdown in the manufacturing process, to decouple manufacturing and assembly line in case of setup optimized production in machining areas, or to cover different shift models. Final assembly lines are normally mixed model assembly lines and therefore fully flexible concerning the variety of engines or transmissions and need no setup.

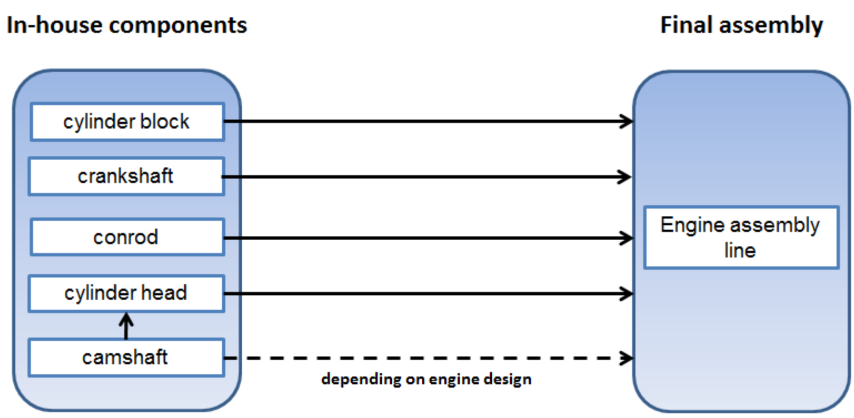

Figure 20 : Basic structure of engine manufacturing (own illustration)

The number of variants of parts in manufacturing is normally low, for example four types of cylinder blocks and five types of crankshafts. The high number of variants at the engine assembly line is generated by variants of the purchased parts that are necessary to fulfill legal requirements like emissions, are vehicle platform driven like fuel systems, or are required by the transmission of the vehicle. Other reasons can be alternative fuels or market requirements like serviceability prerequisites.

In comparison to the engine manufacturing, the basic process stages of transmission manufacturing can be categorized in four main steps: machining (soft), heat treatment to harden the gears, machining (hard) and assembly, as shown in figure 18. The vertical range of manufacturing of transmissions compared to engines is higher due to the high number of gear sets and final drives of the transmissions and the higher number of in house machined parts, which are not reflected in this schematic illustration.

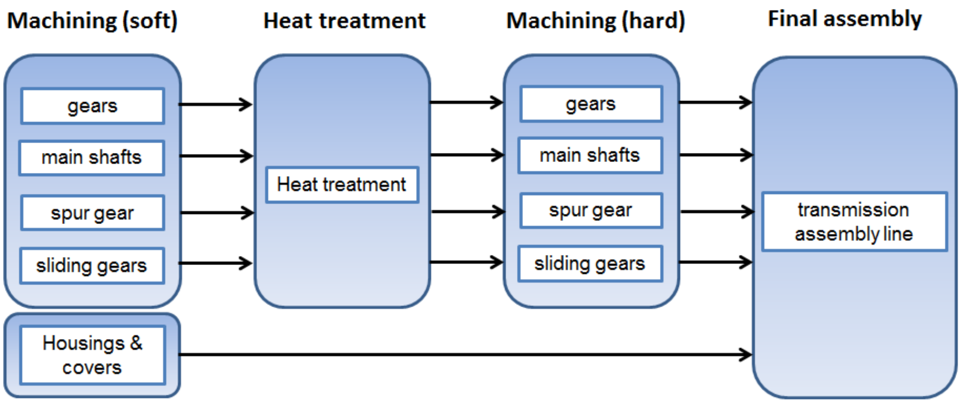

Figure 21: Basic structure of transmission manufacturing (own illustration)

The concept of a hybrid approach for production planning and control, quoted by Klug (Klug F., 2010, p. 389), where centralized push elements and decentralized pull elements are combined to optimize the production flow in vehicle assembly plants is applied as well in powertrain manufacturing. In short, a centralized control center determines an optimized production sequence for the customer orders in the assembly line. The replenishment orders for the upstream component production areas are planned retrograde from the assembly line with decentralized production planning and control methods.

3.3 Planning horizons and planning tasks

Production planning and control is a centerpiece of automotive production to handle variety and complexity. From the time perspective, the hierarchically linked planning tasks can be defined as:

- Long-term: strategic planning
- Midterm: tactic planning
- Short-term: operational planning

As Meyr defined *“long term strategic planning provides potentials, which mid-term planning has to further develop and short-term planning has to implement*”. (Meyr H., 2004, p. 449). The planning data is handled depending on the time horizon on an aggregated level. The three layers of planning horizons can be complemented by the fourth layer of production control, which executes the production schedule according to plan and reacts in case of disturbances to minimize the impact.

The strategic planning is concerned with the long term design of the value chain network in close cooperation of purchasing, production, logistics and sales organization. The strategic planning consists of long-term production planning and budget planning. In long-term production the plans are defined on an annual basis up to ten years in advance. The plans cope with the forecasting of markets based on past data, the vehicles for the markets and the heavy items per vehicle, like engines and transmissions. Directly interlinked with the forecasting and sales planning is the allocation of production capacities. In budget planning the objectives are planned on monthly basis between one and two years in advance. The vehicles per market and plant per year are planned, as well as objectives per plant are defined. During this process, the restrictions like minimal utilization and capacities of plants are considered (Palm D., 2013, p. 151). After the production program of the vehicle assembly plants is determined, the production programs of the powertrain plants are determined (Herlyn W., 2012, p. 167) . The overall yearly production quantities can be considered as volume goals for production and expected production cost targets and earning targets can be derived from the volume targets (Meyr H., 2004, p. 453).The strategic planning has a high importance due to the high investments for the installation of production capacities in automotive industry. Normally the installed equipment is dedicated to particular products and adaption for other products is connected to high cost, or even uneconomic. The installed capacity has to be right sized to cover the whole life cycle of the product (Dörmer J., 2013, p. 33).

The midterm, tactical planning is coping with the planning of production on an aggregated level on a weekly basis from two to six weeks up to one year in advance. The task of master production planning requires a higher level of detail for the generation of a monthly rolling planning on weekly basis. The demand based on customer orders and forecasts is determined on part level for a material requirements planning procedure. The demand of components is communicated to the Tier 1 suppliers as a preview of the quantities to be delivered within the next months (Meyr H., 2004, p. 454).

The tasks of short term, operative planning of mixed model assembly lines are defined as part of the hierarchy of planning of mixed model assembly lines (Boysen N. et al., 2007, p. 761):

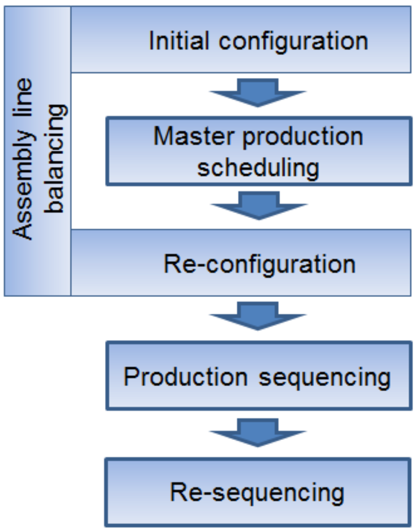

Figure 22 : Hierarchy of planning of mixed model assembly lines (Boysen N. et al., 2007, p. 762)

The task of line balancing is concerned with the configuration of the assembly line and is a midterm planning task. The configuration comprises e.g. the number of workstations, the allocation of tasks to the stations, and the allocation of production factors for the work stations. The line balancing can be executed at the time of the initial installation or a as a re-configuration triggered by design changes or process optimizations.

The relevant tasks in the hierarchy of planning of mixed model assembly lines in terms of short-term production planning and control are as shown in figure 20 Master production scheduling, Production sequencing and Re-sequencing and are discussed in detail in the following chapter.

3.4 Integrated approach of Short-term scheduling and sequencing

Because of the high complexity in a mixed model assembly line due to a high number of production orders and workstations, the short term scheduling and sequencing problem of mixed model assembly lines is normally solved in a two-step-hierarchical process. The basic principle is to decompose the complexity of the overall planning problem into more manageable sub-problems and anticipate the consequences of the bottom-level task at the top-level. The top level task is the master production scheduling, and the bottom level task is the production sequencing, see figure 21. Within the task of MPS, the orders are assigned to a certain production period, normally one day. The maturity of the orders is considered during this planning step. The decisions made in the MPS influence the decision possibilities of the subsequent production sequencing process (Top-Down-Influence).

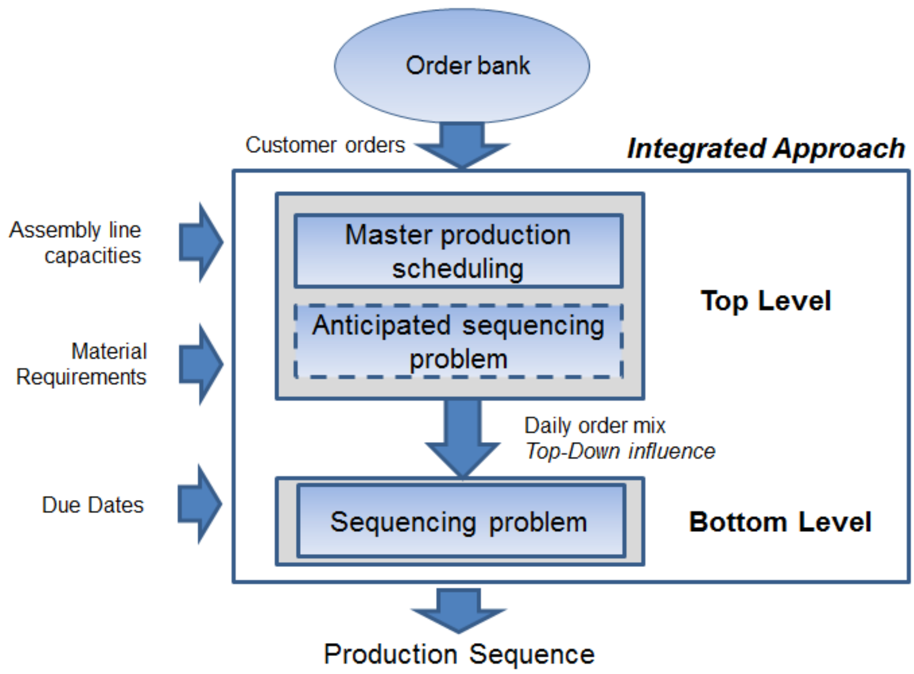

Figure 23 : Hierarchical planning system (Dörmer et at., 2013, p. 50)

3.4.1 Master production scheduling (short -term scheduling)

The task of master production scheduling assigns production orders for individual products to production intervals over a short-term planning horizon of several days or shifts. At that point promised delivery dates, in-house and external production capacities for components and the capacity of the assembly line, which is determined by the line balancing, have to be considered (Dörmer J., 2013). As part of the line capacity, the shift models and the human resources planning have to be included into the master production scheduling process as well. The target of master production scheduling in BTO oriented production is to plan the production dates of the order stock in a meaningful schedule, to that the costs that arrive from the deviation between agreed due date and real production date are minimized (Boysen N. et al., 2007, p. 767). Different concurring planning objectives of master production scheduling can be identified. On the one hand are the objectives, which are straightforward linked to the periods of MPS, and on the other hand the objectives for the anticipated sequencing problem (Dörmer J., 2013, p. 52).

As mentioned above, the objectives of master production scheduling are:

- Promised delivery dates
- Capacity of assembly line
- logistic restrictions of internal and external components

The due date oriented objective is based on the confirmed delivery date. If the powertrain plant fails to deliver on time, the noncompliance could result in worst case in a line stop at a vehicle assembly plant. This situation is not only connected to high costs at the vehicle assembly plant but also linked to a loss of reputation of the powertrain plant. In a mitigated form, the exceedance of a due date, lead to additional logistic costs for accelerated transport of the powertrains. On the other side additional inventory cost incur arise if the product produced is too early. As a consequence, the due dates have to be considered in the framework of the master production schedule planning.

Additionally to the restrictions concerning the parts, the maximum capacity of the assembly line has to be considered. If the maximum capacity is exceeded, a short-term capacity increase with overtime or additional shifts have to be planned. On the other hand, an underutilization of the available capacities has to be avoided due to the sunken cost. A possibility to reduce capacity would be short-time work. A midterm to long-term measure to increase the capacity of the assembly line is the reconfiguration of the assembly line. The MPS is based on the assumption of a fixed number of production takts per period, which is determined by the line balancing. The number of production takts per period can be increased by reconfiguration.

The logistic restrictions of internal and external components are depending on the installed maximum capacity for specific in-house parts or the purchased maximum capacity per planning period at the supplier. The capacity can be adjusted short-term by measures like overtime or short work. In contrast to the complexity of an assembly line, the additional purchasing of machining capacity of in-house components at external suppliers is feasible. This is more a mid- to long-term measure, if the required capacity is not short-term available at a plant with the identical component, or a supplier has a contract for delivery in peak periods.

As mentioned above, the master production schedule is the base for the production sequencing and therefore influencing the output of the production sequencing. As a consequence, the strategy of production sequencing has to be anticipated for the master production scheduling.

3.4.2 Production Sequencing

In general final assembly lines allow the random sequence of variants. But to achieve the logistical targets, a particular production sequence has to be determined. The production sequencing determines the exact sequence of the production orders for each production interval at the final assembly line. The predetermined master production schedule has to be resolved in terms of a detailed production sequence at the final assembly line and the production order is assigned to the dedicated production tact on daily basis. The decisions of the previous master production schedule planning influence and limit the possibilities of the production sequencing because of the top-down influence. Constraints concerning lot sizes, lead times, material restrictions and assembly line capacity like available workforce have to be considered. In vehicle assembly plants, the variability of configuration and the resulting variation of process time per work station much higher than in a powertrain assembly plant. Therefore the exact planning of the sequence has a higher impact on the workload of the workers. The material-oriented sequencing method is well known in powertrain manufacturing. With increasing individualization of powertrains and multi model assembly of engines on one assembly line, these capacity concepts are also for interest in terms of possible sequencing strategies.

In literature for vehicle assembly plants three different sequencing methods are distinguished (Boysen N. et al., 2007, pp. 772-773):

- Level scheduling
- Mixed model sequencing
- Car sequencing

The concept of level scheduling is derived from the Toyota production system and is a material-oriented concept. Level-scheduling targets on the creation of a smooth flow of material in production through a leveled spread of material demand. The upstream component production and suppliers are supplying the assembly line just-in-time or even just-in-sequence. Since the JIT-concept is almost eliminating safety stocks, the assembly line sequence directly affects the production sequence of the upstream component production lines.

The capacity oriented approaches of mixed model sequencing and car sequencing target on the avoidance of resource overload on the workstations of the flow assembly line. Mixed model sequencing is minimizing the overload by an exact schedule which takes the individual workload of every type at the work stations in account. Car sequencing as well tries to eliminate overloads, but it does not consider the detailed workload at work stations. Car sequencing is based on sequencing rules for particular options with a high capacity requirement. Target of car sequencing is to find a sequence, where the sequencing rules are not violated or the violations is minimized (Dörmer J., 2013, pp. 39-41).

3.4.3 Re-sequencing

The process step of production sequencing has fixed the sequence of production orders and the internal component suppliers and as far as necessary in powertrain assembly, the external component suppliers were informed about the production sequence. Sometimes the production sequence cannot be maintained due to unexpected disturbances, which inhibit the execution of the sequence. To cover the impact of the disturbance, a re-sequencing is required. Re-sequencing can be defined as a planned, short-term change of the assembly sequence (Boysen N. et al., 2007, p. 773).

Reasons for the disturbances and the resultant re-sequencing are:

- Missing delivery of parts
- Delivery of defect or suspect parts
- Non-conforming parts in component production
- Machine breakdowns in assembly line or component production
- Short term changes of customer demand (urgent demand)
- Re-work in assembly line

For vehicle assembly lines, the literature distinguishes between “virtual” and “physical” re-sequencing. In case of “physical” re-sequencing the parts are re-sequenced in a storage area, where the parts are sorted and re-sequenced. The target is normally the recovery of the original sequence. The second mentioned method of “virtual” re-sequencing changes the assignment of work piece and order without changing the physical sequence of the parts (Boysen N. et al., 2007, p. 774). From the investment perspective, the “virtual” re-sequencing is much cheaper, because it needs just investment in IT systems, while the “physical” re-sequencing needs an investment in equipment. Both methods can be also applied in powertrain manufacturing for the fulfilment of JIS or JIT supply of the vehicle assembly plants. In contrast to vehicle assembly lines, where the sequence builds an assembly pearl chain which is stable over the complete assembly process, the sequence in powertrain assembly can change due to assembly concept. Depending on the layout of powertrain assembly lines, these have the disposition to destroy the original sequence especially at parallel stations like leak tests or end of line tests, which need a longer cycle time than the planned cycle time of the assembly line. To cover the longer cycle time, multiple stations are arranged in parallel.

Another possible occurrence re-sequencing in powertrain assembly lines is the change of the production sequence before the affected order is physically started at the assembly line. This can happen because of one of the above mentioned disturbances. The impact on the upstream production lines has to be considered.

4 Evaluation of decentralization of PPC concerning short-term scheduling and sequencing at a powertrain plant

Decentralization in terms of Industrie 4.0 is based on the abilities of cyber-physical systems to measure their state, cooperate and render decisions to certain extend on their own. Decentralization in terms of production planning and control is already implemented in today's manufacturing areas with flow production lines. Chapter 4 analyses the current state of decentralization of PPC for the powertrain manufacturing area of Opel Wien. The analysis applies the catalogue of criteria presented in Chapter 2, which seems to be appropriate to evaluate the current state of decentralization and level of autonomous control. The catalogue of criteria has, according to Böse and Windt, an abstract level of definition and was the only systematic valuation system found during literature research. The analysis focuses on the master production scheduling of the assembly line, production sequencing of the assembly line and the production lines and the re-sequencing process in case of disruptions. The interaction between central production planning and control department and the component production departments is considered in the analysis.

4.1 Description of the current state

The analysis of the current state of the level of decentralization of production planning and control, and especially the short term perspective is based on semi-structured interviews with employees of Opel Wien. The interviewed persons are production planners from the production planning and control department and foreman and managers of the component production lines. In addition to interviews processes and structure documentation were also reviewed and discussed. The interviews were also coping with the mid-term planning of material requirements to get an overall picture of the tasks of the program planners. The capacity planning process was out of scope, because the capacity planning process is a long- to midterm process that is normally executed latest two months in advance of the actual production month. Short-term capacity adjustments executed only in exceptional cases, and are not a standard instrument of short-term planning and control. The interviews were documented by written notes of the interviewer.

Prior to the analysis, the engine manufacturing area, the order entry and the midterm material requirements planning are described to give a better overview of the production planning and control sources and tasks. The positioning within the

PPC target system and current IT systems of the PPC department and the production areas are described in short.

Description of the investigated engine manufacturing area

The engine manufacturing area consists of a mixed model assembly line and of six component production areas: cylinder block, crankshaft, camshaft, cylinder head machining and assembly, and two separate lines for connection rod machining. The production orders at the assembly line are consisting of small to large batches and are controlled with an MES system. The assembly line itself has no set up restrictions and is capable to produce in one piece flow. To reduce complexity in the line concerning material delivery and due to type variety restrictions in the unloading area at the end of the line, it is avoided to sequence all possible variants simultaneously. The line layout is designed as a conveyor system with automated and manual working stations. Most of the automatic stations are single stations, except of the test equipment in the line, where two leak tests, respectively four end-of-line test stations, are arranged in parallel. The manual working stations are arranged as manual working areas with up to ten successive working stations. The engines are continuously moving with a constant speed according to the line capacity while the workers are executing their task of assembly. The workload in the manual working stations is leveled out. The major in-house parts cylinder block, crankshaft and cylinder head are ordered via an electronic Kanban system in sequence from the upstream component production and are delivered by a conveyor system. At the end of the line the engines are automatically unloaded into transport racks. The racks are loaded with eight engines of one single engine type. Therefore the engines are not delivered according to a vehicle assembly line sequence for a JIS delivery. The major constraints of the assembly line are the capacity of the assembly line, the material availability and the staffing of the shifts. The staffing of the shifts is relevant, because the produced engine types have a major difference concerning the manual workload between naturally aspirated and turbocharged engines. Shifts which have to assemble turbo charged engines are staffed higher.

The component lines are set up as flow lines. For example the cylinder block line is the most complex line, because it consists of a main line, a bypass line with restricted capacity and variety and two upstream component lines for engine bedplates. The setup cost and setup times for component lines are highly relevant and sequence dependent. The component production starts with the loading of the raw material, which is delivered directly from different foundries. The processing time from raw part to finished component is up to one shift. At the end of the component line is a safety stock of the different types according to the demand of the assembly line. The major constraints of the component production lines are the dependent setup costs, the material availability the stock capacity and limited capacity of upstream sub-component lines.

Receipt of orders and material requirements planning

The powertrain plant in Vienna is using an across the group implemented MRP system to plan the material requirements. The incoming orders for powertrains are derived from a superior MRP system of the vehicle plants by a BOM explosion of the vehicle BOM. The order contains the information of the ordered assembly number, the number of ordered parts, the customer assembly plant and the required due date for shipping. The delivery time between powertrain plant and the ordering vehicle assembly plant are automatically considered by the system, as well as plant shut down or legal holidays. The MRP system delivers a forecast of orders forty weeks in advance on a daily basis.

The material requirements planning task is part of the duties of the production planning and control department. For the forty weeks of the forecasted customer orders in the MRP system a rolling planning and re-planning concerning the deviations of the previous week is executed. The first four weeks are planned on a daily basis and the subsequent weeks are planned on a weekly basis. The MRP planning already incorporates the planned capacities and the constraints of the assembly and the component lines, as well as the constraints of the suppliers and the stock of finished goods. Additional demands for external customers like Aftersales or Product Engineering or provisions for rebuilds of equipment are integrate into the production plans and MRP as well. The uneven distributed customer orders are leveled to the offered capacities in accordance to the demanded due dates. If, due to mayor changes in demand, the capacities would be exceeded, the capacity planning task would be started to solve the mismatch between capacities and demand. The created production order forecast is uploaded into the MRP system and after a BOM explosion sent to the suppliers via EDI, so that they can manage their supply chain.

Positioning within PPC target system

The logistic targets of short lead time of delivery, reliability of delivery, high utilization and low stocks are contradictory. As an optimization is not possible, the company has to define its position within the PPC target system. From a global perspective, the ranking of the four targets was that the high reliability of delivery had the highest ranking for all interviewees, independent of component production line or assembly line as the lateness of delivery of powertrains has high impacts on cost and reputation of the plant. The adherence of the shipment plan, which is directly linked to the production sequence due to low stocks of finished goods, is one of the main KPIs of the plant. The adherence to the production schedule, the build plan, is the second tracked KPI. The deviations to the planned sequence have to be tracked and the reasons for the deviations have to be classified. The second ranked logistic target is the target of short lead time, which supporting the target of due date reliability. The term short lead time itself is one of the five pillars of the implemented production system. The production system is inspired by the Toyota production system and includes the classical lean measures. The third and the fourth position in the ranking of the logistic target system could not be determined as clear as the first ones. Especially for the component production areas with high setup times, high utilization was weighted higher than inventory at the end of the line. The target weighting of the assembly lines is as well to be viewed differentiated. For the transmission manufacturing a higher stock of finished goods is accepted to support the high utilization of the component lines that run optimized setup sequences. The stock level of in-house parts is kept on a lower level by a synchronized production schedule of component lines and assembly. On the other side, the engine manufacturing area is focused on a low level of inventory of finished engines because of the higher value of an engine. To support this strategy, a higher, predefined stock of in-house parts is accepted. For example the asynchronous production of cylinder block line versus assembly line due to the setup costs of the cylinder block line is covered with a higher stock of finished cylinder blocks, while the stock of finished engines is kept low.

Outline of IT System landscape

The applied MRP system and is the common materials management system of the group, including MRP-Assembly supporting assembly plants and MRP-Components supporting component manufacturing plants. The MRP system addresses four functional categories: order management, specifications, internal and external Scheduling, and inventory management. The MRP system itself has no planning, scheduling and sequencing functions.

Two solutions for planning, scheduling and sequencing of the assembly lines are applied. The first solution is the classical spreadsheet-approach, where the production planner uses an excel-tool for the planning and scheduling against the capacities and constraints. The excel tool has EDI functions for the MRP system for import of the orders and export of the planned material requirements. The MRP system then orders the required parts at the suppliers according to the BOM explosion. On the other hand, the excel tool has an EDI to the MES system for the transfer of the assembly line build sequence. The second solution is an advanced planning system, with the main functions of planning, scheduling, sequencing and inbound and outbound monitoring including EDI to the MRP system and the MES.

The implemented MES System is able to handle the main tasks of production planning, production control and shipping. The MES system is executing the predefined production sequence for the assembly line and the progress of every single engine at the assembly line is tracked at defined points. The MES collects data of the equipment and the processes of the assembly line and the component lines. A shipping module is implemented in MES with handles the complete racking and outbound shipping of the engines and gives feedback to the MRP system concerning the order fulfillment.

Mainly spreadsheets are used for the decentralized planning of component lines. The fulfillment of from the planned production schedule of the component lines are tracked in a central database on shift-basis. The root-causes of occurred deviations are tracked in a central database and have to be eliminated to ensure the expected quantity and quality of parts.

4.1.1 Master production scheduling (short -term scheduling)

The master production scheduling task is part of the duties of the production planning and control department. The master production schedule for the assembly line is a two-week schedule that is detailed on a daily basis and on powertrain assembly number. The generation of the Master production schedule is executed with the help of the MRP system and a spread-sheet tool or a advanced planning system. The inputs for the generation of the master production schedule are:

- the two-week dispatching plan forecast
- the actual stock of finished goods
- shift models
- the capacity constraints of the assembly line (shift dependent staffing)
- planned capacities of assembly line and component lines
- the capacity constraints of suppliers
- anticipated sequencing strategy (lot-sizing, sequence dependencies)

The actual dispatching plan is forecasting the shipments of the following two weeks on daily basis and is broken down to the powertrain assembly number.

The master production schedule for the assembly line is further broken down into a two-week master schedule for the component production lines. The daily demands of the components on part number basis are determined from the demands of the powertrains. This two-week master schedule for the component production lines is the planning basis for the component lines. As an example, the camshaft line produces nine types, the cylinder head eight variants and the crankshaft line five variants that have to be planned. The two-week forecast is sent on spreadsheet basis to the production managers of the component production lines and is subject to short term changes driven by changes in production, demand or material availability.

4.1.2 Production sequencing of assembly line and component lines

The investigated powertrain plant is following build-to-order strategy, where the customer decoupling point is located at the beginning of the assembly line. The powertrain is built according to a customer order, while the components for the powertrain are manufactured anonymously. The assembly line and the preceding component production lines are decoupled by stocks of the components. The assembly line is pulling the component from the component manufacturing inventory of finished goods. The stock size is reflecting constraints of the component lines and some safety buffers to contain unforeseen disruptions. The raw material is ordered via the MRP system according to the powertrain production orders. As mentioned above, the component production lines are informed by the PPC department about the two-week master production schedule and the two days production sequence. The planning of the component lines is based on the information about schedule and the agreed sequence of the assembly line.

The sequencing task to create the exact sequence for the assembly line to fulfill the customer demands is normally planned once per day. Production sequence is fixed on a rolling procedure for a frozen period of two days. The daily production sequence contains the sequence for the assembly line, as well as the demand of components. The production sequence is defined on the basis of:

- the actual dispatching plan
- the actual stock situation of the assembled powertrains
- the availability of inbound material
- the capacity constraints of the assembly line (shift dependent staffing)
- Stock of finished production components per line and per part number
- Current WIP of production lines
- Rules concerning lot sizes and type sequence
- Short term changes in demand

The production sequence is agreed in a daily meeting of production planning and control and the production areas. The PPC planner prepares a proposal of the production sequence based on the available data and the previous frozen production sequence. The PPC planner, the foremen and the team leaders mutually commit to a feasible production sequence. In case of conflicts the plan is adapted to a feasible plan that fulfills the requirements of the dispatching department.

The foreman of the component line is planning the sequence depending on:

- the assembly sequence
- the estimated throughput time
- the stock of finished components
- the stocks of raw parts
- The stocks of strategic buffers in the component line
- The constraints of sub-lines as applicable

The strategic buffers in the component lines are placed at selected machinery to cover planned maintenance, setup times and unplanned breakdowns and ensure the high utilization of the equipment. The number of parts of raw parts, strategic buffers and stock of finished products is tracked once per shift. The team leaders of the component production lines are responsible for the execution of the decentralized planned sequence of the component production line. In case of deviations to the sequence, for example triggered by a shortage of raw parts or a breakdown of equipment, the team leader informs the foreman and the problem is escalated to the PPC department. For lines with sequence dependent setup costs sequence rules are applied to minimize the setup costs and time. The decentralized planning and control of the component lines is founded on lean manufacturing concepts that empower the staff at the shop floor and is delegates the concerning PPC tasks to the shop floor.

4.1.3 Re-sequencing in case of disruptions

In case of disruptions that endanger the fulfillment of the production sequence of the assembly line, the causing department has to escalate the information to the PPC planner. The members of the PPC department and all affected manufacturing areas work out a backup plan and which might lead to a re-sequence of the assembly line or a re-sequence of one or more component production lines. The inputs for the Re-sequencing process are additionally to the mentioned input variables of sequencing additionally:

- the expected impact of the disruption in time and capacity
- expected repair time in case of breakdowns
- capacity constraints concerning output in case of a defect of parallel equipment
- detailed priority of dispatching due dates
- delivery date of inbound material

The task of re-sequencing in case of disruptions is for the investigated manufacturing area a special case of the production sequencing task in case of disruptions.

4.2 Evaluation of decentralization in terms of autonomous control

The evaluation of the degree of decentralization is based on the evaluation system of autonomous control which was introduced in Chapter 2.2.4. The catalogue of criteria is applied to the described planning task. From the system structure point of view, the evaluation is categorizing the manufacturing system into three layers: the system element layer of the system element and the interaction with their production environment, the sub-system layer of the component production respectively assembly line and the system layer of the entire manufacturing area. The system elements are the logistic objects, which can be production orders, parts and equipment.

4.2.1 Evaluation of Master production scheduling (short -term scheduling)

The time behavior of the objective system for the short-term scheduling can be described from a global point of view as mostly static as due date reliability is the leading logistic objective for the planning task of short-term scheduling. In case of disturbances the logistic objectives of the PPC department won't change on short notice. The reliability of delivery has in any case the highest priority on system and subsystem level. In this case, the system element is the single production order which has the same logistic objectives as the overall system. The organizational structure of the short-term scheduling is hierarchic. The single elements, the orders, are fully dependent on the central logistic coordination entity since they are the objective of the short-term planning process. The number of decision alternatives of the production planner and his planning tool is limited to some decision alternatives when the daily "buckets" are filled for the master production schedule. The constraints of due dates, material availability and capacities limit the scope of action. The algorithm of decision making of MPS is rule-based, regardless of the usage of the rule-based APS ore the knowledge of the production planner. As the investigated planning task is located in the PPC department, the location of decision making can be rated as on the system layer. From system behavior point of view the short-term scheduling task can be determined as deterministic. It is clearly rule based and the APS system is a linear optimization tool, so the results are reproducible. The location of data storage is centralized, since the MRP and the APS systems are based on centralized servers. The location of the data processing is mostly central, since the MRP system is executed on a central server and only the spreadsheet tool and the APS tool are executed locally on a personal computer that is part of the office network. The interaction ability of the logistic objects is limited to the allocation of their order data that is needed for the planning process. The decision execution criteria of resource flexibility can be rated as less flexible. For this planning task only software tools are used, that can be adapted to some extend to changing needs, like the adjustment of rules that are stored in the APS system. The Identification ability of the system elements is high, since the production orders can be clearly identified. The logistic object has no measuring ability, since it is just virtual existing in the planning system. The mobility level has to be classified as immobile, as the order is moved by IT systems through the process.

The calculation of the Level of autonomous control gives a clear indication that the planning task of master production scheduling is a centralized task. The calculation reveals a result of 64 points, which is only 21% of the maximum possible 303 points for full autonomous control. The statement that MPS is a centralized task could have been predicted without the catalogue of criteria. What is more of interest in this evaluation are the deficits of the planning task concerning autonomous control and the preconditions that are fulfilled to a certain degree.

Criteria category	Criteria	Properties				Weighting of criterion	Fullfillment of criterion	Weighting x Fullfillment
Decision-making criteria	Time behavior of objective system	static	mostly static	mostly dynamic	dynamic	9	0	0
	Organizational structure	hierarchical	mostly hierarchical	mostly heterarchical	heterarchical	12	0	0
	Number of decision alternatives	none	some	many	unlimited	12	1	12
	Type of decision making	static	rule-based		learning	8	1,5	12
	Location of decision making	system layer	sub-system layer		System element layer	15	0	0
	System behavior	elements and system deterministic	elements non-/ system deterministic	system non- / elem. deterministic	elements and system non-deterministic	11	0	0
Information processing criteria	Location of data storage	central	mostly central	mostly decentralized	decentralized	1	0	0
	Location of data processing	central	mostly central	mostly decentralized	decentralized	6	2	12
	Interaction ability	none	data allocation	communication	coordination	14	1	14
Decision execution criteria	Resource flexibility	inflexible	less flexible	flexible	highly flexible	2	1	2
	Identification ability	no elements identifiable	some elements identifiable	many elements identifiable	all elements identifiable	4	3	12
	Measuring ability	none	others	self	self and others	6	0	0
	Mobility	immobile	less mobile	mobile	highly mobile	1	0	0
Calculation according to (Böse F. and Windt K., 2007, p. 68)						Level of Autonomous Control:		64

Figure 24 : Application of catalogue of criteria for short-term scheduling (own illustration)

In the context with Industrie 4.0 the production order already meets the decision execution requirement that all elements are identifiable. From the decision system and the information processing perspective the system element production order lacks the ability to render decisions on its own in cooperation with other production orders in a heterarchical structure. If these abilities would be given, the production order would be a “holon” according to the Holonic manufacturing system, or in terms of Industrie 4.0 a virtual representation of a cyber-physical system. If the constraints like material availability and capacities would be represented as well in a virtual space as CPS, the CPS could bargain the master production schedule on a decentralized basis.

4.2.2 Production sequencing of assembly line and component lines

The planning task of production sequencing of assembly line and the component lines was as well evaluated with the catalogue of criteria. In principle the component lines are planned retrograde based on the short-term schedule and sequence of the assembly line. As in real life is a mutual coordination in place, the two sequencing tasks are aligned between PPC department and shop floor.

The time behavior of the objective system the sequencing for the assembly line task can be described from a global point of view as static. The positioning of the logistic target system is not changing on short notice. The reliability of delivery has in any case the highest priority. The organizational structure of is hierarchic, since the single elements – the production orders – are directly linked to the central logistic coordination. The number of decision alternatives for the production sequencing task is rated as many, because of the high number of variants on the assembly line. Even under consideration of the applicable constraints, a high number of possible solutions for the sequencing problem is feasible. The algorithm of decision making of production sequencing is rule-based, regardless of the usage of the rule-based APS ore the knowledge of the production planner. As the investigated planning task is executed mainly in the PPC department under consideration of the cooperation with the production area foremen, the location of decision making can be rated as on the sub system layer. From system behavior point of view the decision task can be determined as deterministic. The location of data storage is centralized, since the MRP, APS and MES systems are based on centralized servers. The location of the data processing is mostly central, since the MRP system is executed on a central server and only the spreadsheet tool and the APS tool are executed locally on a personal computer that is part of the office network. The interaction ability of the logistic objects is limited to the allocation of their order data that is needed for the planning process. The decision execution criteria of resource flexibility can be rated as less flexible. For this planning task only software tools are used, that can be adapted to some extend to changing needs, like the adjustment of rules that are stored in the APS system. The Identification ability of the system elements is high, since the production orders can be clearly identified. The logistic object has no measuring ability, since it is just virtual existing in the planning system. The mobility level has to be classified as immobile, as the order is moved by IT systems through the process.

Criteria category	Criteria	Properties				Weighting of criterion	Fullfillment of criterion	Weighting x Fullfillment
Decision-making criteria	Time behavior of objective system	static	mostly static	mostly dynamic	dynamic	9	0	0
	Organizational structure	hierarchical	mostly hierarchical	mostly heterarchical	heterarchical	12	0	0
	Number of decision alternatives	none	some	many	unlimited	12	2	24
	Type of decision making	static	rule-based		learning	8	1,5	12
	Location of decision making	system layer	sub-system layer		System element layer	15	1,5	22,5
	System behavior	elements and system deterministic	elements non-/ system deterministic	system non- / elem. deterministic	elements and system non-deterministic	11	0	0
Information processing criteria	Location of data storage	central	mostly central	mostly decentralized	decentralized	1	0	0
	Location of data processing	central	mostly central	mostly decentralized	decentralized	6	1	6
	Interaction ability	none	data allocation	communication	coordination	14	1	14
Decision execution criteria	Resource flexibility	inflexible	less flexible	flexible	highly flexible	2	1	2
	Identification ability	no elements identifiable	some elements identifiable	many elements identifiable	all elements identifiable	4	3	12
	Measuring ability	none	others	self	self and others	6	0	0
	Mobility	immobile	less mobile	mobile	highly mobile	1	0	0
Calculation according to (Böse F. and Windt K., 2007, p. 68)						Level of Autonomous Control		92,5

Figure 25 : Application of catalogue of criteria for sequencing of assembly line (own illustration)

For the component lines, the time behavior is mostly static. This can reasoned with the possibility to include the strategic stocks into the planning task. The organizational structure of is rated as mostly hierarchical, since the single elements – the production orders for the components – are decoupled from central logistic coordination by the decentralized sequencing process. The number of decision alternatives for the production sequencing task is rated as some, because of the low number of variants of the components. The lot-sizing that is driven by setup costs is further decreasing the scope of action, even under consideration of the stocks. The algorithm of decision making of production sequencing for the component lines is rule-based. The location of decision making is located at the shop floor level (the subsystem layer) at the foremen of the component and assembly lines in cooperation with the planner of the PPC department. They decide about the order sequence and the order release at the affected lines and take measures in case of deviations from the planned production sequence. The planning and control task is clearly located at the affected production line and decisions are taken mutually under consideration of the impacts for all production lines. From system behavior point of view the decision task can be determined as deterministic. The location of data storage is mostly centralized in the office network, but the necessary data for the planning process like actual stocks has to be partially gathered offline. The location of the data processing is mostly decentralized for the generation of the sequence. The interaction ability of the logistic objects is limited to the allocation of their order data that is needed for the planning process. For this planning task spreadsheets are used, that can be adapted to some extend to changing needs. The Identification ability of the system elements is low, since the sequence is planned in lots and the individual underlying assembly orders can't be assigned to a dedicated component. The logistic object has no measuring ability, since it is just virtual existing in the planning tool. The mobility level has to be classified as immobile.

Criteria category	Criteria	Properties				Weighting of criterion	Fullfillment of criterion	Weighting x Fullfillment
Decision-making criteria	Time behavior of objective system	static	mostly static	mostly dynamic	dynamic	9	1	9
	Organizational structure	hierarchical	mostly hierarchical	mostly heterarchical	heterarchical	12	1	12
	Number of decision alternatives	none	some	many	unlimited	12	1	12
	Type of decision making	static	rule-based		learning	8	1,5	12
	Location of decision making	system layer	sub-system layer		System element layer	15	1,5	22,5
	System behavior	elements and system deterministic	elements non-/ system deterministic	system non- / elem. deterministic	elements and system non-deterministic	11	0	0
Information processing criteria	Location of data storage	central	mostly central	mostly decentralized	decentralized	1	1	1
	Location of data processing	central	mostly central	mostly decentralized	decentralized	6	2	12
	Interaction ability	none	data allocation	communication	coordination	14	1	14
Decision execution criteria	Resource flexibility	inflexible	less flexible	flexible	highly flexible	2	1	2
	Identification ability	no elements identifiable	some elements identifiable	many elements identifiable	all elements identifiable	4	1	4
	Measuring ability	none	others	self	self and others	6	0	0
	Mobility	immobile	less mobile	mobile	highly mobile	1	0	0
Calculation according to (Böse F. and Windt K., 2007, p. 68)						Level of Autonomous Control		100,5

Figure 26 : Application of catalogue of criteria for sequencing of component line (own illustration)

The evaluation shows that the level of autonomous control that is determined with the catalogue of criteria is higher than the central planning process. The level of sequencing in the component line is a bit higher than for the assembly line, but the expected difference from classical decentralization point of view cannot be evaluated.

The potentials for Industrie 4.0 in terms of production sequencing are manifold. It starts with the introduction of an APS that is based on real-time available data of the dispatching plan, the inbound material stocks and delivery, the capacities and current status of the lines and the real-time status of WIP and stock off semi-finished and finished goods. Today most of the information is not available in real-time, but available in intervals of fifteen minutes, per shift or per day, depending on the information source and importance. One of the mayor benefits of sequence planning and real time-availability of data could be the possibility to reduce stocks in and at the end of the component lines due to an integrated planning and sequencing approach of assembly and component lines.

4.2.3 Re-sequencing in case of disruptions

The Re-sequencing process in the case of the investigated engine assembly line is a special case of the production sequencing. The production orders that are already in process on the assembly line are out of scope of the re-sequencing in case of disruptions. In scope of this process is the re-sequencing of the production orders that are in the queue of the MES to be released on the engine assembly line.

The major difference between the planned production sequencing process and the re-sequencing process is in the application of criteria the number of decision alternatives. This number is reduced to some, because of the limitations that are triggered by the disruption.

In terms of Industrie 4.0 this case seems to have the highest potentials for improvements. In case of real –time availability of data, the CPS can organize a new feasible sequence, or in a more classical way, an APS or MES system can derive a new sequence based on the real-time data of material and equipment. Especially “big data” of former breakdowns that is collected by the CPS can help to optimize the new sequence, because an MES could analyze old breakdowns and their solutions and optimize its solution strategy based on the predicted progress of the breakdown. Based on the redefined sequence for assembly and component production, the impact could be minimized and the logistic objectives could be achieved. The new production sequence would then be available for the staff to be checked and executed or the MES starts the new sequence autonomous.

Criteria category	Criteria	Properties				Weighting of criterion	Fullfillment of criterion	Weighting x Fullfillment
Decision-making criteria	Time behavior of objective system	static	mostly static	mostly dynamic	dynamic	9	0	0
	Organizational structure	hierarchical	mostly hierarchical	mostly heterarchical	heterarchical	12	0	0
	Number of decision alternatives	none	some	many	unlimited	12	1	12
	Type of decision making	static	rule-based		learning	8	1,5	12
	Location of decision making	system layer	sub-system layer		System element layer	15	1,5	22,5
	System behavior	elements and system deterministic	elements non-/ system deterministic	system non- / elem. deterministic	elements and system non-deterministic	11	0	0
Information processing criteria	Location of data storage	central	mostly central	mostly decentralized	decentralized	1	1	1
	Location of data processing	central	mostly central	mostly decentralized	decentralized	6	1	6
	Interaction ability	none	data allocation	communication	coordination	14	1	14
Decision execution criteria	Resource flexibility	inflexible	less flexible	flexible	highly flexible	2	1	2
	Identification ability	no elements identifiable	some elements identifiable	many elements identifiable	all elements identifiable	4	3	12
	Measuring ability	none	others	self	self and others	6	0	0
	Mobility	immobile	less mobile	mobile	highly mobile	1	0	0
Calculation according to (Böse F. and Windt K., 2007, p. 68)						Level of Autonomous Control		81,5

Figure 27 : Application of catalogue of criteria for re-sequencing of assembly line (own illustration)

4.2.4 Analysis of manufacturing system based on catalogue of criteria

In the last three chapters the three planning tasks were analyzed concerning the task of autonomous control. In this chapter the manufacturing system which in the focus of the PPC tasks is analyzed according to the criteria of autonomous control.

The time behavior of the objective system can be described from a global point of view as static. The positioning of the logistic target system is not changing on short notice. The reliability of delivery has in any case the highest priority on system and subsystem level. On system element level, the logistic objective system is static too, because of the lack of decision alternatives for the products and equipment in case of disruptions. As installed machining equipment is dedicated for a certain operation and has no backup solution, the capacity at the concerned station is automatically limited in case of disruptions. The organizational structure of the manufacturing area is hierarchic. Every level has its clear rules and framework of action. A clear escalation process is implemented in case of unforeseen events. The number of decision alternatives for the system element layer is limited. The equipment can only decide on which machine the part has to be processed in case of parallel machines. The workers are depending on the determined production sequence for example to set up the machines or to load or unload buffers in the line. The number of decisions on the sub system layer for production planning as well limited, as the sequence of the component lines is depending on the sequence of the assembly line. The planning task for the assembly line has more theoretically due to the high number of variants of powertrains a high number of decision alternatives, but is in reality reduced to a medium number of feasible sequences. The available capacities, the available material and the dispatching schedule limit the number of possible decision alternatives. The type of decision making is depending on the system layer. The component production equipment has the possibility to identify the parts, depending on the part, by mechanical attributes or 2D-matrix codes. At the assembly line, the powertrain is assembled on a carrier equipped with a RFID system. The decision making ability of the component manufacturing equipment is limited to the execution of predefined rules how to process the part. The part is machined according to the predefined process and then handed over to the next process step. In case that the production line has identical parallel stations, the allocation of the part is rule-based depending on the workload of the machines. If parallel equipment is not available because of maintenance or breakdown, the predefined rules route the part automatically to the available station. The deactivation of a machine normally creates a bottleneck in a leveled flow production line. The staff of the line is instructed to react to the situation according to predefined rules, for example to buffer parts into or out of the strategic stocks of the component line to ensure the parts availability and the high utilization. The procedure the scheduling and sequencing tasks is also rule-based. The rules for the assembly line are implemented in the advanced planning system or executed by the PPC planner. For the component lines the PPC is executed by the staff of the component production. The scheduling and sequencing task is assumed to be rule-based because of the steady state of production. In case of a major change in product design and manufacturing equipment, a learning phase is expected. The location of decision making is located at the shop floor level at the foremen of the component and assembly lines in cooperation with the planner of the PPC department. They decide about the order sequence and the order release at the affected lines and take measures in case of deviations from the planned production sequence. The planning and control task is clearly located at the affected production line and decisions are taken mutually under consideration of the impacts for all production lines. The components themselves have no decision possibility on their own, since they have no ability of interaction decision making. The parts are processed according to the established process plan that is executed by the manufacturing system. The process plan does not allow any deviation of the machining or assembly process steps sequence. From the system behavior point of view the system as a whole is non deterministic. The complexity of the interaction of the production lines and the assembly line, the material availability and the occurrence of minor process disruptions prohibit the exact prediction of the future state of the powertrain manufacturing process. From the system element view, the behavior of the machines and part can be evaluated as predictable, because the interaction between the part and the machine is defined by rules and an unexpected event on the single part is expected to be statistically low.

The evaluation of location of the data storage has to be differentiated between the equipment and the processed part. The data for the equipment is stored centrally for all lines at the MES. The process data for the assembly line is stored locally at the data tag of the carrier while the data of the order sequence for the assembly line is stored centrally at the MES. As the location of the data storage is not that relevant for the evaluation of decentralization, an overall assessment of mostly central data storage is assumed. The location of data processing is mostly decentralized for the system elements layer. The machines are processing the parts and the related data, which is generated by the allocation of the appropriate process through type detection, a 2D matrix code or information from the RFID tag. In case of breakdowns, the machine informs the central MES system and the breakdown is visualized locally via an alarm signal of the ANDON system. The interaction ability of the system elements is very important for a high grade of autonomous control. The logistic objects should be able to communicate and coordinate their activities and cooperate with other logistic objects. On average the highest level of interaction ability that can be found in the component lines is the data allocation.

The resources of the component lines and assembly line are inflexible to adopt to execute different process steps than initially planned. The equipment is optimized for the dedicated process by the means of clamping mechanisms and tools. Some of the machines are specially designed for the specific design of the parts. The identification of the system elements is possible depending on the specific production line with 2D Matrix code. During the assembly the powertrain is linked to a dedicated RFID data tag. The measuring ability of the system elements to measure their current state is highly developed. The equipment can measure its current state and report the state to the central MES. As well process data is generated of the products is generated and applied for process control. The layout of the flow lines does not allow the reconfiguration of the process flow to cope with unforeseen influencing circumstances. The mobility of the resources must be assessed as inflexible as they are moved by a conveyor system.

The manufacturing system consisting of the assembly line and the upstream component lines and has a low degree of decentralization in terms of autonomous control. The manufacturing system is based on the principles of lean production and has a hybrid approach for PPC. The assembly line is planned central by the PPC department, while the component lines plan their schedule and sequence decentralized on their own. Nevertheless the PPC department and the decentralized planning foremen always interact and coordinate their planning with each other. Therefore the complex planning task of the planning of the whole manufacturing area is broken down to less complex planning task for the single assembly and component lines. The split of the PPC task into less complex subtasks requires constant coordination and mutual trust between the involved departments.

4.2.5 Comment concerning the application of catalogue of criteria

The catalogue of criteria was selected to determine the degree of decentralization for the selected planning tasks. Due to due to the mentioned high abstraction level the catalogue of criteria seemed to be an appropriate tool to define the level of decentralization. The application on the current planning tasks revealed that it is focusing very much on the abilities and the level of autonomy of the system element, while the evaluation of the degree of classical decentralization of planning tasks on system or subsystem layer is underdeveloped. The catalogue of criteria is implying a general digital accessibility of decentralized data, which is not always given in a classical production system. The catalogue of criteria can be used in this case for a gap analysis towards autonomous control, but not for the evaluation of a degree of decentralization in classical sense.

4.3 SWOT-Analysis of current state

To determine potential improvement measures, the strengths and weaknesses of the current state and the opportunities and threats of Industrie 4.0 are analyzed based on a SWOT analysis. The objective of the SWOT analysis is the improvement of the planning task to fulfill the logistic objectives under consideration of the influence of Industrie 4.0. The SWOT analyses are based on the analysis of the catalogue of criteria of autonomous control and the interviews.

The strengths are the internal capabilities that may help a company to reach its objectives, while the weaknesses are the internal limitations that may interfere to achieve the objectives. The opportunities are the external factors that the company may be able to exploit to its advantage, while the threats are the current and emerging external factors that may challenge the company's performance. The goal of the SWOT analysis is to match the strengths to the opportunities while overcoming the weaknesses and minimizing the threats (Kotler P. & Armstrong G., 2014).

4.3.1 Master production scheduling (short -term scheduling)

Table 1 : SWOT-Analysis short-term scheduling

Strengths	**Weaknesses**
• Input data available in IT systems • Decisions based on rules • Results are reproducible • Experienced staff • High adherence to due date	• IT: Different sources for data (MRP, capacities, material stocks, constraints, dispatching schedule) • Data processing in external tool
Opportunities	**Threats**
• Optimization of logistic objectives (inventory levels) • Vertical integration of IT systems • CPS could bargain daily bucket based on their logistic objectives and the constraints • Earlier consideration of changes in demand • Better forecast for suppliers • Less effort for PPC department	• Low acceptance because of lack of transparency for PPC planner due to autonomous rendering of decisions • Autonomous control might potentially not deliver added value

The main weaknesses of short-term scheduling can be found in the field of the origin and processing of data in different IT systems. The data has to be transferred between the systems via electronic data interfaces (EDI) and in some cases edited manually. The opportunities of Industrie 4.0 are the vertical integration of the IT – systems that could optimize the data quality and availability. This requirement could be fulfilled today already by ERP and MES systems, that cover the fields of MRP, capacity planning and resources planning. The more advanced approach in terms of Industrie 4.0 would be that the production orders are represented as CPS and virtually can bargain their schedule decentralized with the production resources.

4.3.2 Production sequencing of assembly line and component lines

Table 2 : SWOT Analysis of Production sequencing of assembly line and component lines

Strengths	**Weaknesses**
• Split in centralized and decentralized planning to manage complexity • Based on rules • Results are reproducible • Knowledge of staff • Process is based on lean principles	• Different IT systems as source for data and processing • Data processing in external tools • Status of production & stocks not available in real-time • Quality of communication influences result • Adherence to agreed sequence of component lines is requirement for success of assembly sequence • Safety stocks to ensure due date reliability
Opportunities	**Threats**
• Vertical integration of IT systems • Real time availability of data • Real time planning and control • Integrated planning process for assembly and component lines • Optimization of logistic objectives • Sequencing for JIS delivery to vehicle assembly plant w/o re-sequencing storage	• Low acceptance because of lack of transparency of sequencing process due to autonomous rendering of decisions

Today the planning task of sequencing is divided into the subtasks of centralized assembly line sequence planning and the individual decentralized planning of the sequence of each component line to manage the complexity of the planning task. The first main weakness is the is the broad system topology, where the information about orders and due dates, stocks and dates of delivery of inbound material and internal stocks are stored in different systems and have to be called via EDI or edited manually for the processing. The second weakness is the frequency of renewal of the necessary information, since the data is normally not available in real-time. The information gathered by CPS in an Industrie 4.0 scenario could enable to plan the production sequence for the assembly and the component lines in one planning step. Therefore the actual state of the production and the material has to be known. The information can be delivered by the CPS of the machines and equipment and the online information about the material in process and stocks, as discussed for the application of the cyber-physical production management scenario in chapter 2.3.2.

4.3.3 Re-sequencing in case of disruptions

In this case the se-sequencing in case of disruptions is a special case of the production sequencing problem, so the SWOT will focus on the differences and most important factors in regard to the sequencing task.

Table 3 : SWOT Analysis of Re-sequencing in case of disruptions

Strengths	**Weaknesses**
• Knowledge of staff • Mutual problem-solving process	• Detailed status of production & stocks not available in real-time • Quality of communication influences result • Disruption management process triggered manually
Opportunities	**Threats**
• Real time communication of disruption to all affected departments • Disruption management based on real time availability of data • Prediction models to forecast breakdown impact based on previous breakdowns	• Re-sequencing triggered also for minor disruptions that would have no impact at the end of the day

• MES takes prediction models into account • CPS decentralized render decisions to re-sequence to safeguard adherence to due date	

A disruption in production triggers a problem solving process that also incorporates the problem solving task to maintain production and the production sequence at the assembly line. Today the process of re-sequencing is triggered manually and is depending on the communication between the departments and the availability of input data of for the re-sequencing process. Since the re-sequencing task is in opposition to the production sequencing task an unforeseen task, the real-time availability of data could support the task essentially to develop a feasible solution for the problem. In a cyber-physical production management scenario, the APS/MES system also could anticipate information about former breakdowns to optimize the re-sequencing strategy for the achievement of the logistic objectives, especially the adherence to the delivery date.

4.4 Target concept of short-term scheduling and sequencing in terms of Industrie 4.0

To define the appropriate degree of autonomous control or decentralization in the context of Industrie 4.0 it is first essentially to outline the basic design of the manufacturing system. The outlined target concept is based on the assumption, that the manufacturing system, even under Industrie 4.0 perspective, will consist of a mixed model assembly line and upstream component lines that are designed as continuous flow lines. The production system is based on lean manufacturing principles. A job shop principle for the component lines is not considered because of the high volume and low difference of the variants of the parts. The special-purpose equipment that is needed for many of the machining processes of engine parts, like honing of the cylinders or rolling of the crankshaft, has to be designed dedicated for a design family of parts and therefore the integration of this processes into a job shop would not make sense at all.

As the machining in a continuous flow line limits the decision alternatives limits the decision alternatives of a logistic object during the process, the parts in the component lines need no “intelligence” in terms of autonomous control to render decisions on their own. It is sufficient, when the parts can be clearly identified by a unique identification, like a RFID chip or a 2D matrix code. This is needed to know the exact status of every part in the line and in every buffer that is in the line or in a stock of finished components to have the real time picture of the WIP available for a MES system. The equipment has to deliver its current state to an MES system, as also the inbound and outbound material has to deliver. For the assembly line it would make sense to enhance the mobility of the WIP by the usage of autonomous guided vehicles that can easier optimize the material flow through the assembly line in case of different workload or loss of sequence during build up.

In terms of production planning and control, the recommendation would be to enhance the existing lean manufacturing system with a cyber-physical production management (see chapter 2.3.2) that supports the ERP and APS/MES systems with real-time data and optimization of the system models in the planning tools by analysis of real-time data in the cases of steady state production and also for breakdown-management. The three PPC tasks of short-term scheduling, production sequencing and re-sequencing are discussed in detail in the following chapters.

4.4.1 Master production scheduling (short -term scheduling)

The main improvement of the short-term scheduling can be found in the vertical integration of the current different IT systems for MRP, the planning task either in an APS system or spreadsheet based, and the different sources for the inputs of capacities, staffing planning and the current inventory, as well as the constraints of material availability for internal and external components. The real time availability is in this case not the driver for the vertical integration of the IT systems for the planning system. It is more the consistency of the data and the online availability. The consistency and accuracy of the necessary planning input data of an integrated IT system can be further improved by the integration into the Product lifecycle management. Even powertrains that are planned and produced under serial conditions are faced with running changes on the in-house or supplier parts. The integration of the PPC into the PLM process can improve the integration process of new or changed parts by support of the BOM actualization process and planning of the detailed integration process. This scenario for short-term scheduling is conservative in terms of Industrie 4.0 and autonomous control, could be sufficient so eliminate the main weaknesses of the current state and gain an attractive advantage by application basic Industrie 4.0 features in terms of PPC.
Production sequencing of assembly line and component lines

As the timespan between the production sequencing process and the production order release is within a frozen period of 2 to 3 days, the availability of real-time data gets more important than for master production scheduling. Changes in demand or material availability can be anticipated earlier and with more accuracy in a vertically integrated IT system, that has the ability to optimize the virtual representation of the manufacturing system including the equipment and the material flow. This optimization can be executed by a cyber-physical production management system, as introduced in chapter 2. The main benefit is a central planning tool in an APS that is able to optimize the logistic objectives for assembly and component lines at large. The implementation of the result of the sequencing process should be released by a planner of the PPC department to ensure the acceptance of the production sequence. The setup of the automatic sequencing process based on CPS data has to secure the transparency of the planning process. As the execution of the issued sequences of the component lines is essential for the fulfillment of the assembly line, the execution hast to be tracked in real-time in the MES with the information of the cyber-physical systems.

4.4.2 Re-sequencing in case of disruptions

The Re-sequencing process has the highest benefit of real-time availability of all relevant data, as the re-sequencing in case of disruptions occurs unplanned. The re-sequencing process has to deliver immediately a solution based on the real-time state of production to ensure production and the accordance to the promised delivery dates. The deviation from the promised dispatching date can run up in high costs and in worst case end in a line stop at a vehicle assembly plant, as the powertrains are delivered just in time. An advanced planning system that is based on real-time available CPS data of the MES system can not only recalculate the best possible solution based on the current state of production, but it can also predict the progress of the disruption based on analyzed data of previous disruptions. The CPS of material and equipment would message their current state and the measured parameters of the deviation to the cyber-physical production management system, which then calculates a forecast of the disruption scenario based on previous breakdowns. This disruption models can be integrated into the forecast calculation model of the APS system. The outlined re-sequencing process shall support the PPC department and the shop floor to have a short-term available decision-making basis of scenarios for the fulfillment of the logistic objectives, but should keep the last decision in the hands of the staff.

The outlined application of CPS and Industrie 4.0 is a more conservative approach, which is not based on the decentralized autonomous control and rendering of decisions of the logistic elements. The scenario uses the real-time availability of the relevant data for the planning process and its forecast model optimization in an advanced ERP – APS – MES scenario, as outlined by Schuh (Schuh G. et al., 2013). The idea of the Cyber-physical production management is enhanced by the idea to analyze data of previous disruptions and use these forecasted impacts of disruptions for the re-sequencing process, as the available disruption forecasts are applicable.

5 Conclusions and Outlook

In the framework of this master thesis the concept of Industrie 4.0, PPC and the different aspects of centralized PPC versus decentralized PPC were introduced. Aspects of autonomous control in context with Industrie 4.0 and PPC were outlined. A use case was illustrated and the current situation for in-house production planning and control at Opel Wien was analyzed concerning the grade of autonomous control and a SWOT analysis was performed to work out the potentials for Industrie 4.0.

The first research question was addressing the added value that is generated by decentralized production planning and control systems in the automotive industry based on the example. The added value of decentralized PPC is that the complexity of the planning task is divided into sub tasks that are less complex and are planned and executed in the responsibility of the executing production department. The staff and the foreman on the shop floor are responsible for the production planning and control of their unit.

The second research question was addressing how decentralized production planning and control systems are currently designed and developed in the automotive industry. The current state of PPC in the investigated powertrain plant is a hybrid system, where the assembly line is planned centrally by the PPC department and the upstream component lines are planned retrograde at the shop-floor in mutual cooperation with the PPC department. In this case the decentralization is a classical decentralization, where the responsibility for PPC is delegated to the executing unit on organizational level. In terms of autonomous control the degree of decentralization is low, as the system elements have normally not the ability to render decisions more or less on their own. The highest priority within the target system of the logistic objectives has the adherence to the delivery date, followed by the objective of short lead time.

The third research question was facing a potential decentralized design of a production planning and control system for a powertrain assembly plant of the automotive industry in terms of Industrie 4.0. The outlined target concept is based on the assumption, that the manufacturing system will consist of a mixed model assembly line and upstream component lines that are designed as continuous flow lines. The outlined application of CPS and Industrie 4.0 is a more conservative approach, which is not based on the decentralized autonomous control and rendering of decisions of the logistic elements. The scenario uses the real-time availability of the relevant data for the planning processes and its forecast model optimization in an advanced ERP – APS – MES scenario, as outlined by Schuh (Schuh G. et al., 2013). The idea of the cyber-physical production management is enhanced by the idea to analyze data of previous disruptions and use these forecasted impacts of disruptions for the re-sequencing process, as the available disruption forecasts are applicable.

Today the input data of the planning tasks of short-term scheduling and sequencing is derived from different IT-systems that have to interact via EDI. In an Industrie 4.0 scenario the planning tasks will benefit from the vertical integration of the IT system landscape that could optimize the data quality and availability for the planning processes. The closer the planning task is to the order release, the more importance has the actuality of the available data. The real-time availability of data through CPS could enable the planning of the production sequence for the assembly and the component lines in one planning step to optimize the logistic objectives. The task of production sequencing could be optimized by a continuously optimized model of the manufacturing system. The highest benefit of real-time availability of data and vertical integration is expected for the unforeseen task of re-sequencing in case of disruptions. In opposition to the current manually triggered procedure, the real-time availability of data could support the task essentially to develop a feasible solution. In a cyber-physical production management scenario, the APS/MES system also could anticipate information about former breakdowns to optimize the re-sequencing strategy for the achievement of the logistic objectives, especially the adherence to the delivery date. The transparency of the automatic (re-)sequencing process has to be secured to ensure the acceptance of the result by the planners and the shop floor.

The master thesis tried to investigate the production planning and control tasks of short-term scheduling, production sequencing and re-sequencing of an automotive powertrain plant and to outline a potential application of PPC in terms of Industrie 4.0. The concept of Industrie 4.0 is based on cyber-physical systems that enable the logistic objects to render decisions on their own to a certain degree. The evaluation of the level of autonomous control for classically centralized or decentralized planning tasks does not lead to the expected evaluation of decentralization. The evaluation according to the applied catalogue of criteria implies a minimum of decision-making ability on system element level, while the decision ability for classical PPC is located on system or sub-system level. The SWOT-analysis of the current state gives more indication about the possibilities of Industrie 4.0 for the PPC tasks. The closer the planning task is to the execution on the shop floor, the higher are the advantages that can be generated through the application of Industrie 4.0 technologies. The optimization of the logistic target objectives like the reduction of the WIP while maintaining the high accordance to the delivery date through a higher transparency of the production can be one of the major benefits of Industrie 4.0 in this use case.

The concept of Industrie 4.0 and the underlying concept of cyber-physical systems and cyber-physical production systems are still at the beginning of their development for the real implementation in manufacturing. The concept of Industrie 4.0 and has manifold possible applications for PPC that derive from the real-time availability of data and decentralized decision making on system elements level, but the possibilities are today far away from the state to be fully investigated. The next years will exhibit if the theoretical advantages of Industrie 4.0 can be realized in the expected extent. For the author the master thesis was a very fascinating journey through the topics of Industrie 4.0 and Production planning and control in theory and practice at the investigated powertrain plant that gave deeper insights in current trends in manufacturing and practical application of PPC.

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