1 Introduction

1.1 Motivation

An old joke is often told in regard to dysfunctional organisations: A new leading manager is hired and trained by his predecessor. In the last meeting, the predecessor gives the new manager three envelopes and tells him to open one, whenever the organisation is in trouble. In the beginning, all goes well, but after some time the organisation becomes less and less effective. Our manager decides to open the first envelope – there is a piece of paper inside with a single word written on it: "Decentralise". Following the advice, the manager decentralises many of the organisational structures and everything works like a charm. However, after some more time passes, the organisation finds itself in trouble yet again. Our manager decides to open the second letter, which also contains a piece of paper with a single word written on it: "Centralise". The manager also follows this advice, and the organisation enters another time of thriving success. When the organisation fell into a slump a third time, the manager opens the last envelope. This time there are four words on the piece of paper: "Write three new envelopes".

While being light-hearted and being told in many varying versions (c.f. Randall 2005), this joke illustrates a common problem: It still remains elusive, why an organisation should employ a centralised or a decentralised structure. Furthermore, it remains unclear which structure is overall more efficient. Instead of having valid reasons to perform a centralisation or a decentralisation project, executing such a project may be based on assumptions that still may lead to overall improvements. However, this might be based on the corresponding business processes within the organisation being adapted to suit current challenges better, instead of being a direct consequence of the (de-)centralisation itself. Similar effects can also be observed when considering the historical developments in regard to production planning and control (PPC) tasks. In 1979, Harrington introduced the concept of Computer Integrated Manufacturing, which includes the vision that all PPC related tasks should be fulfilled by integrated computer systems, ranging from Engineering and Design to granular operational tasks such as Production Scheduling or Production Monitoring (Harrington 1979). However, information technology (IT) of the time was often not capable of handling the amounts of data and different information types efficiently. In consequence, many enterprises started to make use of lean manufacturing concepts, particularly following the principles introduced by Toyota, as originally proposed in 1977 (Sugimori et al. 1977). Using these concepts, usually, a decentralised inventory and production control combined with mostly manual information sharing was employed, oftentimes not making use of IT support at all. In recent years, concepts regarding the digitalisation of manufacturing – such as Industry 4.0 - built on both movements.

Hence, they were establishing end-to-end IT concepts while making use of decentralised decision-making and centrally available information (Kagermann et al. 2013). However, despite these developments spanning several decades, it remains unclear, whether a decentralised or a centralised approach should be employed – especially when considering operational PPC tasks (Kuprat et al. 2015, p. 14).

In the following, the term PPC architecture will be employed. Analogous to a common definition of software architectures, a PPC architecture is hereby defined as the overall structure that performs the PPC tasks, the components that form this structure, and the rules that characterise the interactions between these components (c.f., Jones 1993). A PPC architecture can incorporate different kinds of PPC system structures (which are presented in detail in Chapter 2.3). In a heterarchical PPC architecture, the system elements are structured in a heterarchy, i.e., they "they possess the potential for being ranked in a number of different ways, depending on systemic requirements" (Crumley 2015, p. 1). For example, a machine as an element of a heterarchical PPC architecture could normally follow planning instructions provided by a superordinate planning software, while also being capable of taking its own planning decisions when the instructions by the superordinate software cannot be executed, e.g., by manufacturing a product earlier than planned, because of missing materials for the creation of the product that was intended to be manufactured first instead.

The question regarding the use of decentralised or centralised approaches furthermore shows itself in a dichotomy between science and practice. Now, scientists investigate, design and recommend the usage of heterarchical PPC architectures for well over two decades (Schreiber 2013, p. 2). In contrast, enterprises in practice mostly still rely on traditional hierarchical and thus centralised architectures instead, not making full use of the capabilities of modern production equipment (Gronau 2019a, p. 31). On a generic level, the advantages of heterarchical PPC architectures are often accepted by practitioners. However, these advantages are also often hard to measure and thus it is difficult to convince decision-makers to permit the considerable investments needed to reap the rewards from this change in paradigms.

One example is the project Production 2000+, which was initiated in 1996 and encompassed one of the first prototypical implementations of an agent-based, heterarchical production control architecture in a small production step within an engine plant of the Daimler Chrysler AG (as it was called at the time). This prototype was established in 1999 and employed during real manufacturing operations in parallel to more commonly centralised and hierarchical approaches (Sundermeyer and Bussmann 2001). However, a follow-up roll-out of the heterarchical PPC architecture onto further areas of the production system was never established, as business-wise no improvements in key performance indicators could be assessed.

Furthermore, scientifically reported qualitative advantages like an increase in flexibility and productivity could not be facilitated within the overall production system – as the preceding and the succeeding production processes were not capable of making use of similar flexibility measures, they constrained this production step and no advantageous effects could be achieved (Schild and Bussmann 2007). Hereby, Flexibility describes the ability of a system to adapt itself to changing influences within pre-defined corridors. This encompasses production processes, material flows and other logistics functions (Wiendahl et al. 2007, p. 786).

Despite these shortcomings, the reasons that led researchers to recommend more heterarchical PPC architectures did not diminish over time. The number of components of manufactured goods is growing, their lifecycle is decreasing in length, the number of variants is rising and the requirements of customers in regards to manufacturing times and product quality are growing still (Schuh et al. 2017). Considering the case of Germany, several further factors influence the traditional strong industrial sector of the country. High wages, energy costs and dependencies on foreign material suppliers cause exceedingly high manufacturing costs compared to other competing nations. In order to ensure the competitiveness of the German industrial sector despite these issues, the German Government called the aforementioned Research initiative "Industrie 4.0" into existence (Kagermann et al. 2013). One of the main goals of Industry 4.0 is to empower industrial enterprises to produce customer-specific goods in small lot sizes with (nearly) the same efficiency as current mass production. This goal is intended to be achieved through the introduction of autonomous interconnected systems, particularly Cyber-physical Systems (CPS) (machines, that encompass actuators to influence their environment, sensors to recognise their environment, embedded systems to compute decisions locally and communication capabilities to send and receive information), that within a given situation are capable of controlling their own activities (Vogel-Heuser 2017).

The introduction of CPS into manufacturing plants, in turn, enables the implementation of heterarchical PPC architectures without further investments on the shop floor itself: The machines will already be accessible through data networks and contain embedded systems that might be used to determine and/or execute local instructions. Therefore, Industry 4.0 can be seen as an enabler of heterarchical PPC architectures. Worldwide, investments into the digitalisation of production systems can be observed, which also encompasses the main capabilities of CPS (Ignat 2017). Nevertheless, organisations in practice oftentimes do not make use of these capabilities as of yet (Gronau 2019a, p. 31). Paradoxically, in this context the historical dichotomy between science and practice has been reversed: On the one hand, practitioners consider decentralisation as one of the most challenging, but also potentially rewarding design elements of Industry 4.0 (Hermann et al. 2016). On the other hand, the topic receives comparatively low attention from a scientific point of view.

In a review from 2021, only four out of 130 analysed sources regarding Industry 4.0 principles focus on decentralised decision-making (Cañas et al. 2021, p. 6). Cañas et al. also claim that “It is noteworthy that the principles of decentralised decision makings, intelligence/awareness, technology and business within the I4.0 framework have been mostly dealt with to date.” (Cañas et al. 2021, p. 2). However, they neither explain this statement further nor provide sources for it. Consequently, this statement does not refute the need for further research as it has been derived within this thesis. Instead, decentralised decision-making and control are defined as a key constituent of Industry 4.0 by several authors (e.g. Roth 2016; Hermann et al. 2016).

While the goals and the innovation potentials of Industry 4.0 are generally accepted, the concrete implementations in practice within the German manufacturing sectors are not making comprehensive use of these concepts yet. In comparison, other countries such as China make far greater progress in the digitalisation of their production systems (Naumann 2021, 202f). However, this difference creates increased competitive pressure, which in turn might induce a further implementation of Industry 4.0 related concepts in practice within the near future.

Production systems in Industry 4.0 are envisioned to be fully automated, self-organizing and self-controlled (Schuh et al. 2017). Consequently, the behaviour of the production system would emerge at runtime and thus cannot be predetermined completely. For example, when concurrent machines negotiate among each other which machine will process the next incoming production order, the resulting manufacturing times depend on the given state of each machine at a particular point in time, which in turn is dependent on the outcomes of past suchlike negotiations and machine states. In consequence, the exact point in time, when a specific good will finish manufacturing, is unclear. In turn, manufacturers, therefore, cannot make use of established concepts like just-in-sequence anymore (Bochmann et al. 2016, p. 184). Overall, this lack of predetermination makes the behaviour of the production system harder to understand and practitioners generally show reservations regarding employing suchlike system architectures (Schreiber 2013, p. 2). In conclusion, such a completely decentralised system might not always be desirable in practice. To balance both the predeterminable qualities of centralised approaches and the flexibility of decentralised ones, the phrase “as central as possible, as decentralised as needed” was coined (Leitao and Restivo 2008).

The complexity of a production system is the main reason for the introduction of heterarchical PPC architectures according to literature (Windt et al. 2008; Gronau 2019b). The term complexity also allows another perspective on Industry 4.0. Generally, complexity management can be considered a “strategic issue for companies to be competitive” (Vogel and Lasch 2016).

The aforementioned effects such as increasing customer requirements in turn increase external factors influencing the complexity of a production system and have been doing so continuously for several decades (Schuh et al. 2010). Indeed, this rise in complexity is considered to be one of the biggest challenges for manufacturing companies in general (ElMaraghy et al. 2012). Therefore, the investigation of manufacturing complexity has matured into its own research field, in which various factors influencing the complexity of a production system, so-called “complexity drivers", have been identified (c.f. Vogel and Lasch 2016). In this context, the introduction of Industry 4.0 can be seen as an effort to increase the internal complexity within a company to match the increased external complexity, which a company cannot directly influence (Bauernhansl et al. 2014b). This overall rise in both internal and external complexity is, in turn, another factor for the introduction of heterarchical PPC architectures. After all, decentralised decision and planning models are of far less computational complexity, as they also ensure a decomposition of centralised models into smaller sub-models. Thus, it is easier to include additional parameters and decision variables in such models and make use of decision alternatives, that could not be employed within centralised decision and planning models, such as the inclusion of additional flexibility measures (Anderson and Bartholdi 2000). For example, instead of following a linear plan of processes that have to be performed to manufacture a specific product, the decision models could contain relevant decision variables and parameters for varying processes, that could lead to the same goal, such as the usage of laser versus traditional milling (Windt and Jeken 2009). These varying production processes may also incur different production times and costs that have to be considered during planning.

While a vast number of publications in all three depicted research fields (heterarchical PPC architectures, Industry 4.0 & Manufacturing Complexity) exist, works discussing the link between these in detail are sparse. A set of projects that focused on predicting the optimal level of decentral and autonomous control in the context of complexity assessments was the SFB 637 “Autonomous Cooperating Logistic Processes: A Paradigm Shift and its Limitations” led by the University of Bremen (c.f. Scholz-Reiter et al. 2004). In publications of this project, a causal relationship between a manufacturing systems complexity, the level of autonomous control of its elements as well as the achievement rate of logistic objectives was presented, as shown in Figure 1 (Philipp et al. 2006; Böse and Windt 2007; Windt et al. 2008).

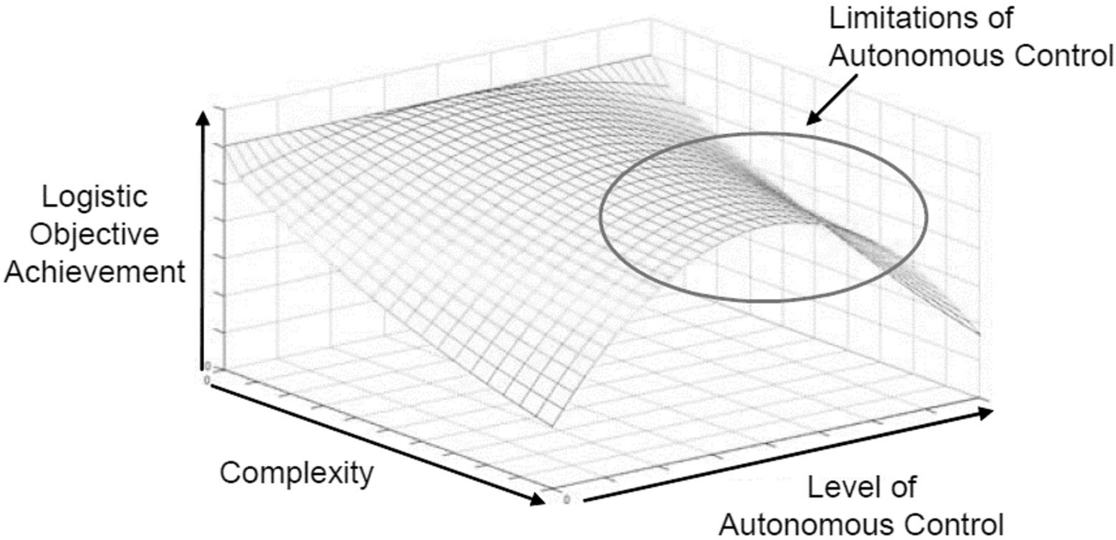

Figure 1: Application Potentials and Limitations of Autonomous Control Systems (c.f. Philipp et al. 2006)

Autonomy describes the ability of a system element, to independently take decisions on its own. Furthermore, the system element, therefore, needs to be independent of other system elements in its environment (Scholz-Reiter and Freitag 2007, p. 712). Consequently, the degree of autonomy of a system element describes the capability of said element to take decisions on its own, in contrast to following decisions of higher-ranking system elements (such as within a hierarchical system). Therefore, the higher the degree of autonomy within a system, the more decentralised it is as well (which is why these terms are commonly used in conjunction in literature). Extraordinarily complex production systems will generally contain more decision alternatives, which in turn can better be covered by decision models employable in a more decentralised and heterarchical system structure. Therefore, it seems intuitive, that an increase in a production systems complexity increases the achievement rate of logistic objectives of heterarchical PPC architectures, as only the decomposed decision models within suchlike architecture can handle the high amounts of decision alternatives caused by the high complexity. In contrast, less complex systems profit from centralised decision models more strongly, as these can optimise the links between the different system elements more efficiently.

However, establishing and verifying the details of such a relationship is a challenging task for several reasons: Firstly, the level of autonomous control – and thus the degree of decentralisation of the overall production system - itself is difficult to determine. The different architectures for heterarchical PPC found in literature allow for various degrees of decentralisation, but no continuous function or even qualitative ordering regarding their associated degree of decentralisation exists. Secondly, similar issues arise when trying to quantify a production system's complexity. The overall production system complexity is influenced by a number of different factors (i.e., complexity drivers).

For example, the variance (difference in demand amount) and variability (difference in demanded goods) of customer demands as well as the depth of production (number of production steps), the breadth of production (the number of products or production steps that can be processed in parallel) and the various types of flexibility potentials that can be made use of (Bozarth et al. 2009)[1]. However, not all factors are easily measurable and quantifiable, e.g., when considering flexibility measures (Sethi and Sethi 1990). The production system´s complexity is also influenced by the interrelation between these factors, hence measuring the factors on their own is not sufficient to predict the optimal level of autonomy (Vogel and Lasch 2016; Gronau 2019b). Furthermore, while it may generally be possible to establish a link from the production systems complexity (for example measured by selecting a set of complexity drivers) towards the computational complexity of PPC tasks, the influence on the runtimes of the associated planning problems is not clearly quantifiable either (Siegmund et al. 2015).

Most known planning problems, especially scheduling problems that consider at the very least capacities and setup costs, are NP-hard by nature and can be extremely time-consuming to solve, particularly in worst-case scenarios (Drexl and Kimms 1997). However, modern information systems can employ many algorithms that might even solve large problem instances of these planning problems in short timeframes (Koch et al. 2011; Gleixner et al. 2021). Nevertheless, the used state-of-the-art algorithms often exhibit vast variations in runtimes for different planning scenarios (Hutter et al. 2014). Especially when considering operational decision-making, these runtimes can potentially exceed the available time to make such decisions. This especially happens when considering various decision alternatives, e.g., whenever considering making use of flexibility potentials. Heterarchical architectures can handle such planning models better, as a decentralisation of the planning task also implies a decomposition of the underlying planning models (Kelly and Zyngier 2008). Therefore, investigating the link between production system complexity and the computational complexity of planning problems may yield important insights into determining, when to make use of heterarchical PPC architectures. Other works focusing on determining the complexity of production systems concerning the need for heterarchical PPC architectures do not analyse the relation to the computational complexity of planning problems further, additionally motivating the need for research into understanding these relationships (c.f., Gronau 2019b; Scholz-Reiter et al. 2006).

[1] A more detailed analysis of factors influencing the complexity of a production system is provided within chapter 4.2.

The influence of the different complexity types and interrelations between them cause two important trade-offs between hierarchical and heterarchical PPC architectures as discussed in the context of the research project Smart Face (c.f. Böckenkamp et al. 2017, 545f): “*Truth vs. Probability*”, describing the aforementioned decision between a foreseeable, deterministic behaviour of the production system (called “*truth*” by the original authors) in comparison to the emergent behaviour of heterarchical and/or autonomous entities (called “*probability*” by the original authors) and “*Pre-planned Sequences vs. Maximum Flexibility*”, detailing the trade-off between a deterministically planned centralised system behaviour considering the interactions between the different sub-systems (called “*pre-planned sequences*” by the original authors) and the potential advantages a more detailed localised planning could entail by being capable of making use of further flexibility potentials (called “*maximum flexibility*” by the original authors) (Hülsmann and Windt 2007; Böckenkamp et al. 2017, 545f). Ultimately however, both of these trade-offs cover the same aforementioned decision between a predetermined system behaviour and one whose behaviour is emerging at runtime – in other words, a novel architecture was developed, that ultimately dealt with the same issues, as numerous architectures in the past (e.g., the PROSA and ADACOR Architectures (c.f., van Brussel et al. 1998; Leitão and Restivo 2006)). However, in the presentation of the SMARTFACE architecture, these similarities to past works were not discussed thoroughly (c.f., Böckenkamp et al. 2017). Instead, new mechanisms were introduced without analysing, whether they are already present in previous works. This can also be observed in other publications that propose heterarchical PPC architectures for usage in modern digitalised production systems (e.g., Ebufegha and Li 2022; D’Aniello et al. 2021; Didden et al. 2021). This indicates that practitioners and scientists alike do not have the capability, to easily identify already existing heterarchical PPC architectures in literature. Additionally, they are unable to quickly categorise their features. However, such a categorisation is needed to be capable to compare different heterarchical PPC architectures with each other and to be able to select promising candidates for application in practice. Furthermore, practitioners might also be unable to match the technical capabilities of a given production system to the requirements of a specific heterarchical PPC architecture, ultimately making it impossible to estimate the efforts required for the implementation of a suchlike architecture. Therefore, further research is required to alleviate these gaps in knowledge and to provide decision support for the selection of a heterarchical PPC architecture, to reduce reservations of practitioners against the usage of suchlike architectures.

Finally, the frequency in which heterarchical PPC architecture introduction projects are performed is likely to increase in the future. Production systems are traditionally rather static, as investing in new equipment and changing the underlying processes is an expensive matter.

Thus, the decision for a heterarchical PPC architecture can be taken in a strategical timeframe and is often considered as an unstructured process, to be answered e.g., by specialised consulting projects. The vision of Industry 4.0, however, implies reconfigurable production systems, that can adapt to the changing environment and customer demands in a flexible manner (Hees et al. 2016). As mentioned before, the usage of a heterarchical PPC architecture is oftentimes a prerequisite for such flexibility. Furthermore, the technical capabilities introduced through the implementation of Industry 4.0 concepts serve as an enabler for the implementation of heterarchical PPC architectures. Thus, the task of delineating the different centralised and decentralised planning architecture elements might be performed more often for different sections of a manufacturing company to match the more rapidly changing environment that modern production systems operate in. However, the unstructured nature of such projects also makes executing them slow and cumbersome, because the required processes must be determined first. The existing literature also provides no implementation approaches suiting heterarchical PPC architectures, necessitating further research in this area. It follows, that the unstructured way of decision-making regarding heterarchical PPC implementation projects should be replaced by a more methodological approach that guides and supports practitioners in suchlike projects. This may also serve to reduce reservations of practitioners towards heterarchical PPC architectures in general, as the effort required to perform an implementation project can be estimated more precisely.

Based on the previous considerations, the research objective (RO) of this thesis can be summarised as follows:

RO: Provide decision support for the complexity-based selection and implementation of heterarchical PPC architectures.

Hereby, the thesis will focus on discrete production (as heterarchical PPC architectures are particularly suited for small series or batch manufacturing) considering the requirements and potentials of modern production systems provided through digitalisation, in particular in the context of Industry 4.0 and related movements. In the following, three research questions serving to guide the research activities towards this overall objective will be derived.

Generally, two reasons for the use of heterarchical PPC architectures exist. Either the required information to perform centralised planning is not available, or the computational complexity of the task requires a decomposition of the planning problem, as decisions can otherwise not be made within the required timeframe – e.g., when hard or soft real-time requirements are in focus. Hereby, a classical decomposition in a hierarchical structure is still insufficient, as such a structure also requires planning adaptations on the superordinate level and consequently causes longer planning cycles.

For the task of operational production planning information availability – at least in theory – is not an issue, as it would be preferable to solve any issues which limit the willingness to make the information available within the same organisation. Therefore, the design of specialised architectures that work with the available, specifically shared information is not required in this case, unlike the case of supply-chain-wide decentralised network planning (where cooperating enterprises of equal power are interested in not unveiling detailed information about their production systems). Instead, established PPC architectures from literature can be used, which offer sufficient capabilities to decompose the centralised and/or hierarchically organised planning problems into less complex heterarchical ones. However, as mentioned before, a link between attempts to measure production system complexity and the computational complexity of the corresponding planning problems has not been established yet in literature (c.f., Windt et al. 2008; Gronau 2019b). Therefore, the first research question aims to analyse this link (RQ):

RQ1: Can the computational complexity of the corresponding production planning problems for a given production system be predicted?

Schreiber argues that it is impossible that an architecture that is “optimal” in any sort or form exists, due to the different influences in the production environment and the interrelations between the planning problems, the PPC architecture, the production system and its environment (Schreiber 2013, p. 27). Compared to e.g., the employed planning problems, the architecture itself has only a limited influence on the resulting manufacturing performance.

This claim can be substantiated by performing simulation studies akin to those proposed (but not executed or at least published) in the context of the aforementioned research project SFB 637 (Philipp et al. 2006). In order to explore the impact of different heterarchical PPC architectures on a manufacturing systems performance, a direct comparison between an older heterarchical PPC architecture, ADACOR (c.f. Leitão and Restivo 2006), and an architecture developed in the context of Industry 4.0, SMART FACE (c.f. Böckenkamp et al. 2017) was performed by the author of this thesis. Both heterarchical PPC architectures were implemented within the simulation framework “Anylogic”. Using identical planning data from a manufacturing enterprise in the automotive supply industry and employing identical standard formulations of related planning problems, the simulation served to evaluate the performance of both PPC architectures next to each other. As an example, Figure 2 depicts the differences in the setup times and idle times using both heterarchical PPC architectures.