Abstract

In this thesis, we develop a framework for the reactive scheduling of flexible manufacturing systems based on model predictive control (MPC). We integrate the modeling and scheduling of a flexible manufacturing system in a common framework, in which the flexibility of the system can be exploited, the modeling effort is minor, and guarantees for the resulting behavior of the manufacturing system are provided.

The framework is specifically designed for manufacturing systems intended for the production of customer specific goods, which is motivated by the concept of Industry 4.0. In this context, the machines are assumed to have a known set of capabilities and the products have a known set of required production steps. Based on a modular description of the manufacturing system, which comprises multiple machines and which is intended to produce a variety of customer specific goods, the production steps have to be assigned to the machines in the best possible way respecting their capabilities. This modular production system offers flexibility, which can only be exploited by a suitably designed scheduling framework as the one proposed in this thesis.

The basis of this framework is a description of the manufacturing system in the form of a flexible job shop. In order to cover a wide range of possible application cases and introduce flexibility from the start, the problem description is kept general and modular. Therefore, there is the possibility to deduce numerous widely discussed scheduling problems as special cases of the proposed problem description, all of which can also be considered in the developed framework.

From the modular description of the flexible job shop, a Petri net model is automatically generated by means of specifically designed algorithms. The dependencies between the different parts of the problem description are captured in the Petri net graph, while it preserves the flexibility of the problem formulation. This is achieved by representing the possible decisions in the manufacturing system through the different possibilities to fire the transitions in the Petri net. In accordance with that, the marking of the Petri net represents the status of the manufacturing system and restricts the possible decisions according to the dependencies in the production problem. Moreover, the algebraic description of the Petri net is well suited for a system theoretic analysis and the application of MPC.

Through the automatic conversion of the production problem, the MPC scheme developed on the basis of the Petri net model retains the properties of the original problem formulation. Incorporating the economic objective of the manufacturing system into the cost function employed in the optimization problem solved in the MPC scheme allows to pursue the economic goal in the MPC based scheduling framework. Through analyzing the properties of the manufacturing system and its algebraic rep-

resentation, we are able to prove the recursive feasibility of the MPC problem and the completion of the production problem through the proposed scheduling scheme. By considering feedback from the system, the MPC is able to react to unexpected events and changes in the manufacturing system.

The proposed framework is able to make optimal use of the manufacturing units in a flexible manufacturing system for the production of customer specific goods. The advantages of the framework are its applicability to a wide range of scheduling problems, its ability to model and to exploit the available flexibility in the manufacturing system for economically optimal operation, and its guarantee to complete the production problem.

Deutsche Kurzzusammenfassung

Ein Framework für die modellprädiktive Regelung in der flexiblen Produktionsplanung

In dieser Arbeit wird ein Framework für die reaktive Produktionsplanung von flexiblen Fertigungssystemen mittels modellprädiktiver Regelung (Englisch: *model predictive control*, MPC) entwickelt. Wir vereinen dabei die Modellierung eines flexiblen Fertigungssystems mit der Produktionsplanung und -regelung in einem gemeinsamen Framework, in dem die Flexibilität des Systems ausgenutzt werden kann, der Modellierungsaufwand gering ist und systemtheoretische Garantien für das resultierende Verhalten des Fertigungssystems gegeben werden können.

Motiviert durch die Entwicklungen in der Industrie 4.0 wird das Framework speziell für Fertigungssysteme entwickelt, die für die Herstellung kundenspezifischer Produkte konzipiert sind. In diesem Zusammenhang wird davon ausgegangen, dass die Fähigkeiten der Maschinen und die für die Herstellung der Produkte erforderlichen Produktionsschritte bekannt sind. Ausgangspunkt ist eine modulare Beschreibung des Fertigungssystems, das aus mehreren Maschinen besteht und in dem eine Vielzahl von kundenspezifischen Gütern hergestellt werden sollen. In einem so konzipierten Produktionssystem müssen die zur Herstellung der Produkte erforderlichen Produktionsschritte jenen Maschinen zugeordnet werden, die sie aufgrund ihrer Fähigkeiten unter den gegebenen Rahmenbedingungen am effizientesten produzieren können. Dieser modulare Aufbau des Produktionssystems bietet eine große Flexibilität, die es durch eine geeignete Produktionsplanung auszunutzen gilt, was das in dieser Arbeit entwickelte Framework ermöglicht.

Ausgangspunkt des vorgestellten Frameworks ist eine Beschreibung des Produktionssystems in Form eines flexiblen Job-Shops. Um ein breites Spektrum an möglichen Anwendungsfällen abzudecken und schon bei der Problembeschreibung die Flexibilität zu berücksichtigen, wird das Problem sehr allgemein und modular formuliert. Die Problembeschreibung umfasst daher zahlreiche in der Literatur betrachtete Produktionsplanungsprobleme als Spezialfälle und ermöglicht es, diese im entwickelten Framework ebenfalls zu betrachten.

Aus der modularen Beschreibung des flexiblen Job-Shops wird mittels speziell entwickelter Algorithmen automatisch ein Petri-Netz-Modell generiert. Dieses behält die Flexibilität der Problemformulierung bei und in seiner Graphenstruktur sind die Restriktionen und Abhängigkeiten berücksichtigt, die das Produktionsplanungsproblem beinhaltet. Die Markierung des Petri-Netzes repräsentiert den Zustand des Produktionssystems und die Möglichkeiten, wie die Transitionen schalten können, stellen die möglichen Entscheidungen im Produktionssystem dar. Die algebraische Beschreibung des Petri-Netzes ist gut für eine systemtheoretische Analyse und die Anwendung von MPC geeignet.

Bei der automatischen Transformation des Produktionsproblems in die MPC-Formulierung werden die Eigenschaften der ursprünglichen Problemformulierung beibehalten. Durch das Einbeziehen des ökonomischen Ziels des Produktionssystems in die Kostenfunktion, die bei der Optimierung im MPC-Algorithmus minimiert wird, wird das ökonomische Ziel bei der MPC-basierten Produktionsplanung explizit berücksichtigt. Auf Basis der Analyse der Eigenschaften des Produktionssystems und seiner algebraischen Darstellung kann garantiert werden, dass das MPC-Problem, welches dem entwickelten Produktionsplanungsverfahren zu Grunde liegt, zu jeder Zeit lösbar ist und dass das Produktionsproblem durch den MPC-Ansatz fertig gestellt wird. Durch die Berücksichtigung von Informationen, die aus dem System zurückgeführt werden, kann die MPC-basierte Produktionsplanung auf unerwartete Ereignisse und Veränderungen im Produktionssystem zielgerichtet reagieren.

Das vorgestellte Framework zur Produktionsplanung ist in der Lage, die Produktionseinheiten in einem flexiblen Fertigungssystem, in dem kundenspezifische Aufträge erfüllt werden, in der bestmöglichen Art und Weise einzusetzen. Die Vorteile der vorgeschlagenen Methode sind, dass sie für eine Vielzahl verschiedenartiger Produktionsplanungsprobleme einsetzbar ist, dass sie in der Lage ist, die verfügbare Flexibilität zu modellieren und im Produktionssystem auszunutzen, um einen wirtschaftlich optimalen Betrieb der Anlage anzustreben, und dass sie das Produktionsproblem garantiert fertigstellt.

Chapter 1

Introduction

1.1 Motivation

Industrial production systems are facing the need to stay competitive in a changing world. In the modern society, where the basic needs of the customer are increasingly satisfied, innovation cycles are getting shorter and the products are adjusted to the specific needs of individual customers. In order to account for this development, the fourth industrial revolution has been proclaimed in Germany and is now being implemented by industry worldwide. This endeavor is called *Industry 4.0* and it exploits emerging new technologies, mainly from the field of information and communication technology, with the goal of developing smart factories that account for customers' individual wishes and generating new business models [39]. Especially networking and digital communication capabilities are employed in manufacturing units and are considered as drivers of this development and expected to revolutionize industry. Smart factories with ubiquitous communication between all components are envisioned to produce smart products that know by themselves how they have to be produced [39].

This environment of flexible interconnections between the participants requires novel strategies for the scheduling of the increasingly dynamic manufacturing system. The production scheduling is challenged with the goal of enabling the production of highly individual goods at the same cost as mass production in order to stay competitive [14]. This challenge is in direct continuation of the history of production scheduling, which started at the end of the 19th century, when the product variety in the individual manufacturing facilities increased [31]. The increasing complexity of the production system already at that time led to the organized production planning based on the ideas of Frederick W. Taylor and Henry L. Gantt. Dedicated planning offices were introduced and the production schedules were represented in the form of Gantt charts, which are still widely used. The underlying production problems can be formulated as optimization problems and the invention of electronic computers in the second half of the 20th century facilitated their solution through the automatic execution of complex optimization algorithms. By that, the time to create production schedules and to optimize the production processes could be reduced. Due to the complexity of the scheduling problems, mainly techniques to find suboptimal solutions in a short amount of time were developed [24]. Those include various heuristics and in modern days also concepts using machine learning techniques attract increasing attention [13, 85]. For exact solutions of scheduling problems, mathematical programming based on mixed integer program (MIP) formulations of the scheduling problem are used, but they are limited to small and medium sized problems [15, 24]. They suffer from the high complexity of the underlying problems and the resulting large computation times and sometimes even infeasibility for the case of large problem instances, but have the advantage that they offer the possibility to provide rigorous guarantees. The more detailed review of the history of production scheduling by Herrmann [31] reveals that since the advent of information technology, the development of novel scheduling techniques was always driven by the increase in computational power, making previously intractable problems solvable.

Also in the current development of Industry 4.0, the increase in communication and computation capabilities offers the basis for the development of novel scheduling techniques. The new capabilities foster the development of modular and flexible production paradigms such as skill-based engineering, cyber-physical production systems and digital twins of all components involved in the production system [2, 61, 70]. They exploit the miniaturization of computational units combined with communication interfaces to form self-aware components that interact with each other. Such modular units need to be orchestrated by advanced scheduling techniques.

Although there is no particular joint development of Industry 4.0 and scheduling research, both developments go in a similar direction [70, 84]. The increasing complexity of the manufacturing environment motivates both the development of new concepts in Industry 4.0 and the further development of scheduling techniques. For the two lines of research to mutually benefit, a unified framework for data exchange and execution of manufacturing tasks is needed to allow the implementation of scheduling algorithms in Industry 4.0 environments [84].

The general goal of industrial manufacturing is to deliver the highest economic outcome while consuming the least possible resources and thereby optimize the manufacturing process [39]. In a dynamic manufacturing environment as it is envisioned in Industry 4.0, this requires optimization of the manufacturing system and in particular of the production schedules. The production of individual goods needs to be achieved by the highly flexible machines in an optimized fashion in order to be competitive. The products are aware of their required production steps and the machines provide their capabilities. Both are available in a digital representation of the production system by means of their digital twins [61]. In the digital environment, the optimization of the production can take place and the optimal production scheduled can be computed in real-time based on the most up-to-date information about the manufacturing system. The optimization goal, although it usually considers an economic objective by trying to maximize the profit generated with a given production system, might also consider further criteria as the reduction of waste or the environmental impact [69]. Through repeated optimization of the production schedule, the flexibility of the manufacturing system can be exploited by reacting to the request for new products to be scheduled and unexpected changes in the production system and its surrounding.

In order to support this development, we exploit the strengths of mathematical programming based scheduling techniques to provide mathematically rigorous guarantees for the optimization of the production schedule in real-time and propose a model predictive control (MPC) based approach. MPC is a modern control technique that has a wide variety of applications ranging from complex plants in process industry to trajectory tracking for autonomous vehicles [22, 50]. It heavily relies on a mathematical model of the system to be controlled. Based on this model and a measurement of the most recent information from the system, a finite horizon optimal control problem is solved and only the first part of the optimal solution is applied as an input to the system. This procedure of measuring the state, solving the optimal control problem and applying the input is repeated at every time instant in a closed feedback loop [67]. The models being used can be linear, nonlinear, time or parameter varying or even distributed among multiple controlled agents [28, 52, 67]. In an MPC approach to production scheduling as proposed in this thesis, based on a system model the behavior of the production system is predicted and optimized over a finite time horizon into the future. From the resulting optimal decisions in the planned production process, only the decisions for the current time instant are applied to the system. Through measurements in the production system and information on new jobs that have to be scheduled, feedback is introduced and the optimization is repeated in the next time step based on the new information. The advantages of MPC are, besides the sound understanding due to the wide range of research and applications, that it solves an underlying optimization problem and therefore tends towards an optimal system behavior with respect to a desired performance criterion and that it is able to explicitly consider state and input constraints. Another advantage, which is obvious when it is applied to classical control problems but is relevant with respect to the use of MPC as scheduling technique, is the fact that it has an inherent feedback mechanism while optimizing the system behavior. By repeatedly solving a finite horizon optimization problem it is computationally efficient with respect to solving the entire scheduling problem at once.

In this thesis, we propose a framework in which the advantages of MPC are exploited to incorporate instanteneous feedback from the production process into the digital decision making on the scheduling of the plant and optimize its future behavior. We contribute with control theoretic methods toward a real-time optimal production in flexible manufacturing systems (FMSs) intended to fulfill customer specific orders motivated by Industry 4.0. In the proposed framework, we combine the MPC based scheduling scheme with automatic model generation for production systems. Thereby, not only changes in the state of the system, but also in the system structure can be considered during runtime. We exploit the modularity of the production system as basis for the formulation of the model generation algorithms, which can also incorporate changes of the system at a later point in time into the system model. The model generation, which is based on a formulation of the manufacturing system in the form of a flexible job shop (FJS), results in a Petri net (PN) model, which stands out for its simplicity and the resulting linear state space model, which can be used in MPC.

To summarize, the goal of this thesis is the formulation of a framework for the scheduling of a manufacturing system, which exploits the flexibility of the production system and provides theoretical guarantees based on a mathematical model. Through the interdisciplinary research, we combine the strengths of multiple research fields to achieve an improved overall scheduling system. The modularity of the manufacturing system modeled as an FJS is exploited in the automatic model generation. The resulting system model in the form of a PN is directly suitable for MPC. Trough the inclusion of an economic objective in the computation of the MPC control law used as the scheduling scheme, the economic aspect of the manufacturing system is considered. The result of the scheduling scheme are manufacturing decisions, which are directly applied to the system. The flexibility of the manufacturing system is respected in the flexibility of the framework through the model generation and the feedback interconnection. A more detailed description of the contributions of this thesis is provided after describing related literature from the adjacent research fields.

1.2 Research Topic Overview

The research presented in this thesis spans multiple disciplines, starting from its motivation in Industry 4.0, over the problem formulation as a scheduling problem and the modeling in the form of a Petri net, until the solution approach by means of model predictive control. Therefore, to outline relevant existing results for this interdisciplinary research, we briefly present related literature in the respective areas with a focus on the intersection between the different fields. Parts of this research overview are based on [88] and are adopted in parts literally.

Industry 4.0

The development of Industry 4.0 started in Germany with the attempt to improve the competitiveness of German industry. To this end, in 2011 a working group was initiated that identified relevant research directions and outlined concepts for the future of industrial production [39]. They did not only focus on the industrial production itself, but also on adjacent topics as, for example, business and society, that are in strong relation to the industrial developments. In their final report, they deduced recommended actions to stay competitive in the future industrial environment which have been further developed since then. One of the key factors they identified is the flexibility and adaptability of the manufacturing environment to meet changing customer demands and volatility in markets [84]. To coordinate future research activities, the "Plattform Industrie 4.0" was initiated. From this starting point, research was conducted in various directions and new initiatives with similar scope were started in many countries, for example the Industry IoT Consortium (formerly Industrial Internet Consortium) in the United States, which joins forces with the Plattform Industrie 4.0 to coordinate their developments on specific topics, e.g., on the concept of the digital twin [8].

Research results on the different topics in Industry 4.0 from theory and practice are summarized in [34], which is an online handbook that is continuously updated over time and new printed editions will be released repeatedly.

In the context of this thesis, especially the research and developments on manufacturing systems with regard to Industry 4.0 are of interest. The development of intelligent manufacturing systems is motivated by the requirement of improved productivity and faster adaptation to the demand of customers [93]. In a review on different approaches and technologies towards intelligent manufacturing systems in Industry 4.0, Zhong et al. [93] identified flexibility of the manufacturing systems as one of their key features required to achieve this endeavor. They discuss multiple technologies that allow to increase the flexibility of a manufacturing system, as for example service-oriented architectures and radio-frequency identification (RFID). One way of achieving flexibility is the introduction of service-oriented or skill-based engineering [54, 62], leading to a modular orchestration of the manufacturing units enabling the coordination of autonomous agents in Industry 4.0 scenarios. Malakuti et al. [54] formulate a skill-based engineering model with the goal to enable mass customization, meaning that customized products can be created at the same cost as in mass production. Based on this model, further research question are posed on the coordination in manufacturing systems, which can be formulated as a modular scheduling problem between autonomous product agents and autonomous machines. In a similar approach to robot programming, the commands to a robot or machine are commanded in an abstract way, such that the linking between different production steps can be performed on a high level [29, 79]. This became popular in the field of robot programming, where the high level of abstraction is provided to the user in order to simplify the usage of versatile robots [2, 30, 32, 47, 71, 83].

To summarize, Industry 4.0 is a recent research initiative to which we contribute with methods from systems and control theory in order to exploit the increasing flexibility of manufacturing systems with the goal of enabling mass customization.

Production Scheduling

Scheduling problems arise in various different fields, e.g., the scheduling of takeoffs and landings on airports, the scheduling of games in sports tournaments or the scheduling of computations on a computer processor [35]. Various methods to solve a wide variety of scheduling problems are well studied and fill many text books, for example [10, 66]. In our research, we focus on the scheduling in industrial production and in particular on the scheduling in modular and flexible manufacturing systems that are intended for the production of individual goods and able to react to disruptive events, as for example machine breakdowns. This is in contrast to other branches of production scheduling, where the same products are repeatedly scheduled on the same machines, as it is usually the case in chemical production scheduling [76]. For the representation of scheduling problems for FMSs, formulations as job shop (JS) problems and generalized versions of it are used [6, 70], which we formally introduce in Section 2.2.

The class of problems considered in this thesis is a further generalization of the FJS, which itself is a generalization of the JS. We classify the considered problem class as job shop with multi-purpose machines and sequence flexibility (JMPMSF) in Section 2.2 according to a classification scheme introduced by Graham et al. [26]. For the solution of scheduling problems for the FJS mainly heuristics are used [13, 63], and also the even more complex JMPMSF, is mostly solved by means of heuristic approaches [7, 40, 82]. However, since we are not only interested in finding a solution for the problem but also to rigorously analyze it, we develop a mathematical modeling technique of the scheduling problem. Therefore, we do not review the heuristic approaches in more detail.

As mathematical models of the FJS, different MIP models have been developed, which were evaluated by Demir and İşleyen [15] with respect to their complexity and computational efficiency when minimizing the total makespan of the FJS. With respect to a mathematical model of the JMPMSF, Birgin et al. [6] and Özgüven, Özbakır, and Yavuz [63] present two different mixed integer linear program (MILP) models to find a schedule that minimizes the makespan.

Özgüven, Özbakır, and Yavuz [63] extended a well-known MILP model by Manne [55] for the minimization of the makespan which is computationally effective compared with other MILP models of the JS problem [15]. Through two extensions they augment the mathematical model from the JS to the JMPMSF. A simulation study confirms the applicability of the proposed model.

Birgin et al. [6] propose another MILP model for the JMPMSF based on a notion of the problem description as a graph. The problem description generalizes the one considered by Özgüven, Özbakır, and Yavuz [63] by allowing so called "Y-jobs", in which two intermediate products, which are started separately, are combined at a later stage. In a comparison with the model presented in [63], Birgin et al. [6] conclude that their model has less optimization variables and performs better most of the times in an extensive simulation study.

The practical relevance of the JMPMSF was shown by Lunardi et al. [51], who consider a JMPMSF from online printing industry that is subject to additional challenges. They present a MILP and a constraint programming model for it, after providing a concise literature review on the JMPMSF.

To react to changes and disturbances in the production system, reactive scheduling techniques are used. There are two basic approaches to react in those cases, which have been investigated by Fahmy, ElMekkawy, and Balakrishnan [18] for the case of FJS scheduling. On the one hand, the existing schedule can be taken as a starting point and it is adjusted to incorporate the required changes, for example by inserting new jobs in an existing schedule. On the other hand, changes in the system can trigger a restart of the scheduling completely from scratch. Kopanos et al. [43] investigated the influence of rescheduling including the effect induced by the change of the schedule. They include rescheduling penalties to decrease the frequency of rescheduling actions, mitigating their negative effects and making the rescheduling scheme more suited for scheduling problems in practice. Research on rescheduling and reactive scheduling in industrial production continues to these days and still gives rise to novel results. In a recent paper, McAllister, Rawlings, and Maravelias [56] analyze the effects of rescheduling and propose an improved MPC scheme for chemical production scheduling.

Motivated by the characteristics of Industry 4.0, Rossit, Tohmé, and Frutos [70] introduced a novel alternative to those general approaches for production rescheduling. They propose a smart scheduling system, which is able to react to disruptive changes in the manufacturing system and uses *Tolerance Scheduling* to generate production schedules in a JS environment. At first, a nominal schedule is computed and only events changing the quality of this schedule significantly will trigger a rescheduling. To determine when rescheduling is necessary, deviations of the delivery dates of the different products are determined, which still lead to an acceptable level of suboptimality with respect to the original schedule. Only if the real process deviates more than those values, rescheduling is initiated.

This brief review on scheduling problems is by no means exhaustive. We only considered the most relevant papers on the scheduling problems arising in Industry 4.0 and in particular on the FJS and the JMPMSF. As models for those problems, we specifically considered mathematical descriptions and thereby excluded the majority of literature, which solves the FJS and the JMPMSF by means of heuristics. To draw a brief conclusion, despite scheduling being a mature research field, there are still new problems to be considered and novel approaches are developed for their solution. A significant challenge in production scheduling is the interaction between the scheduling scheme and the real system. The disruptive effects in the production system together with changing external conditions in Industry 4.0 pose a major challenge for the scheduling schemes applied in future manufacturing systems.

To summarize, existing literature mainly covers specific scheduling problems and most frequently they are solved by means of heuristics. In this thesis, we propose a modeling and production scheduling framework that can be applied to the JMPMSF, which is a relevant class of scheduling problems in practice and generalizes further scheduling problems, in particular the frequently considered JS. The proposed framework and allows to give rigorous guarantees of the closed loop interconnection with the real system.

Petri nets

Petri nets (PNs) have been introduced by Carl Adam Petri in his Ph.D dissertation on the communication in automata [64]. He defines PNs as graphs through which discrete markers called *tokens* are moved according to specific rules, as we explain in more detail in Section 2.3. The main application of PNs is in the description of discrete-event systems and therefore they are an integral part of many books on this topic, e.g., [11, 73]. Starting from the initial description by Petri [64], many formalisms extending the original description have been introduced, for example timed PNs, high-level PNs and stochastic PNs [59]. The appeals of PNs are their compact representation of systems with a large state space, their modularity and that they have a graphical as well as a mathematical representation [73]. Especially their modularity makes them well suited as a modeling technique in this thesis.

PNs have been applied to model FMSs in an Industry 4.0 context. Long, Zeiler, and Bertsche [49] use extended colored stochastic PNs to model the flexibility of a production system intended for the mass production of customer specific products. They extend the classical notion of PNs by further elements in order to represent the production system and its flexibility. The resulting model can be used to support the decisions on batch sizes, product variants, delivery time and prices of the products. Latorre-Biel et al. [45] propose an object PN model as decision making support for FMSs in the frame of mass customization and Industry 4.0. They employ complex tokens, which are themselves modeled as PNs, to represent the products. Those product tokens are moved through an overarching PN representing the FMS. The two kinds of PNs are synchronized by requests for services from product agents to the machines. The modular composition of the two types of PNs jointly represents the production system. Those two publications are only exemplary to show how PN models are used to represent Industry 4.0 scenarios. They particularly underline the importance of the modularity and variability of PNs, which help to model the proclaimed flexibility of the manufacturing systems.

Yadav and Jayswal [90] provide a review of several modeling techniques for FMSs which involves, among others, PN models. They show that PN models have a wide variety of applications and are employed for deadlock avoidance, minimization of the makespan, performance analysis, scheduling and control of the FMS. They highlight that the usefulness of the PN model lies in the well-structured nature of the relationships between the modules in the PN and the simplicity of the resulting linear state space description. PN descriptions for scheduling problems of FMSs usually either directly use a real-valued production time in a timed Petri net [73], or ignore the time information and describe the production process as a discrete-event system, which again results in a non-timed PN as introduced by Petri [64].

As a conclusion, Petri nets proved to be a versatile modeling tool over the last decades. In addition to their original definition, they offer a wide variety of extensions that increase their expressive power at the expense of their clear and simple representation. Applications for the decision making process in FMSs and the modeling of FJSs indicate their usefulness in an Industry 4.0 context, for which they are particularly suited due to their modularity. In accordance with those insights from literature, we exploit the useful properties of PNs by employing them as modeling tool in the developed framework for the scheduling of FJSs.

Model Predictive Control

Model predictive control has been established as a versatile control scheme, in which an open loop optimal control problem based on a system model is repeatedly solved in a feedback interconnection with the real system. It is well studied, has a wide range of applications in various industrial fields [22], and several textbooks describe the results in different branches of MPC theory [28, 67]. The existing results form a mature theoretical basis and cover a wide range of different system classes. Most results on MPC consider the cases of setpoint stabilization or trajectory tracking, in which the cost function employed in the open loop optimal control problem is designed in a particular way that leads to the desired stability or tracking guarantees. In contrast to that, beyond the stabilization problem, the economic objective of the industrial plant would be the natural choice for the cost function. Investigation on the direct applications of such economic cost functions in MPC problems are considered in the theory on economic MPC. For this branch of MPC research, there exist various different approaches that are summarized in a survey by Faulwasser, Grüne, and Müller [19]. In this thesis, we employ MPC for the particular goal of reactive scheduling of FMSs modeled as PNs. To this end, we focus on the interface between MPC, production scheduling and PNs in the remainder of this literature overview.

In scheduling problems in manufacturing systems, discrete decisions to influence the future evolution of the system have to be taken. This results in discrete valued systems, for which MPC is not applied very often due to the computational complexity of the underlying optimization problem [12]. In order to simplify the optimization, Zhang, Liu, and Pannek [92] relaxed the integer constraint that arises in a dynamic capacity adjustment problem for a production system with reconfigurable machine tools which exhibits JS characteristics. Based on the relaxed formulation of the optimization problem, they optimize the capacity adjustment by means of MPC. The question how the underlying integer assignment problem can be solved based on the solution of the relaxed problem is left as an outlook. An MPC approach for the scheduling of reentrant manufacturing lines motivated by semiconductor manufacturing was considered by Vargas-Villamil and Rivera [81], who optimize the long-term behavior of the system modeled as a discrete time flow model with respect to a multi-objective cost function by means of linear programming. The result of the MPC solving the linear program is fed to a subordinate controller which computes the integer valued short-term decisions and applies them as control input to the plant. Cataldo, Perizzato, and Scattolini [12] use MPC for the scheduling in a machine environment with parallel identical machines that are fed through transportation lines of different lengths. Their goal is to maximize the production output while limiting the energy consumption. The resulting optimization problem is a MIP assigning speeds to the machines and binary inputs to the transportation system. The three publications [12, 81, 92] show at exemplary cases how MPC can be applied to discrete decision processes. They illustrate that the discrete decisions can either be relaxed and decided in an underlying problem, or directly included in the optimization problem.

In contrast to problems in scheduling and discrete manufacturing where MPC is rarely used [12], it has a variety of applications in supply chain management and especially in process industry, where continuous models naturally arise [19, 41, 76, 77]. Due to the large body of knowledge on various properties and different implementations of MPC schemes, it became a well-established control method in this area [22]. In literature which is more closely related to the topic of this thesis, MPC is applied for the scheduling of a chemical production systems in which binary decision variables are used [56, 76]. In the considered MPC problems, the possible tasks are assigned to the available production units in order to satisfy an external demand or to optimize the economic performance of the system. The problems considered in this line of research investigate the scheduling in chemical batch production systems with a previously known set of products.

In the work by Subramanian, Maravelias, and Rawlings [76], a discrete time state space model of a chemical production system is proposed. Based on this model, they provide an MPC formulation of the scheduling and batch sizing problem for the production system. It is shown how typical scheduling disruptions and further characteristics of scheduling problems, as for example resource handling, can be included in the state space model. They suggest to consider scheduling problems as economic MPC problems and to develop new scheduling algorithms that include classical notions from MPC theory, in particular recursive feasibility, closed loop performance and stability. In a recent publication, McAllister, Rawlings, and Maravelias [56] built upon this result and investigated production rescheduling with the goal of reducing frequent changes in the planned schedules by means of rescheduling penalties included in the cost function employed in the economic MPC problem. They have a particular focus on retaining theoretical properties despite the penalties on the rescheduling actions. The provided results rely on suboptimal MPC theory, in which the optimal solution does not necessarily need to be found in order to achieve the desired guarantees. McAllister, Rawlings, and Maravelias [56] are able to guarantee a certain level of performance with respect to a known reference schedule. This reference schedule is used as terminal equality constraint in the MPC problem to ensure recursive feasibility and closed loop performance with respect to the given cost function. Since the MPC inherits the performance of the reference schedule as worst case performance bound, a good reference schedule created by an elaborate heuristics is guaranteed to lead to good performance that can only be improved by the MPC.

Using systems and control theory to analyze and influence PNs is common in the literature [3, 25], and also MPC techniques are used [38, 53, 78]. In the context of MPC for PNs, usually either continuous or hybrid PNs are considered from the start, or *fluidification* of the PN is used. Fluidification means that the tokens, which in an ordinary PN are discrete markers that are moved through the PN, are considered to be a fluid. Thereby they can be represented by real numbers instead of integers relaxing the integer constraint usually imposed on the PN. Instead of a discrete state vector and discrete inputs to the system, a continuous state vector is considered and the input continuously controls the flow of tokens through the PN. This flow can usually only be in one direction and is limited by a maximum flow rate. Similar to the application of MPC to scheduling problems, the relaxation is used to avoid a high dimensional state space and thereby simplify the optimization problem [53, 78]. It is known that this adaptation changes the properties of the PN and that it is mostly suited for models with a large number of tokens [68, 75], which is why it is not suited for the problems discussed in this thesis.

In conclusion, there exists a solid basis for the application of MPC to various problem classes. A wide range of theoretical results can be exploited in the attempt to provide the desired guarantees for a given system class. With the help of simplifying relaxations, problems in production scheduling and for the control of PNs have been solved by means of MPC and theoretical guarantees can be given. For the control of JMPMSFs and for discrete PNs, the application of MPC to influence the discrete decisions in order to achieve a desired goal constitutes an open research question, which is considered in this work. As outlined in the following section, the goal of this thesis is to create a framework which allows to exploit the flexibility of an FMS motivated by the needs of Industry 4.0 and to provide guarantees through the application of MPC for its production scheduling.

1.3 Contribution and Outline of the Thesis

With this thesis, we contribute to the field of production scheduling for FMSs with methods from model predictive control (MPC) by developing a framework that links the description of the scheduling problem through automatic model generation with its solution methodology by means of MPC. In this framework, we unite the model generation and the solution of the scheduling problem based on the model. This is particularly useful to exploit the flexibility of the manufacturing system due to the possibility to react to changes in the real system by model adaptation or reactive scheduling. In the following, we outline the structure of this thesis and describe the main contributions of each chapter.

Chapter 2 - Background and Preliminaries

In this chapter, we provide a brief explanation of the most relevant concepts from related fields for the contributions of this thesis. At first we introduce some basics from Industry 4.0, in particular the digital twin and skill-based engineering, which lead to the main assumptions taken throughout the rest of this work. As the second main field, we give an introduction to production scheduling. In this context, we explain the most important technical terms and lay a special emphasis on the systematic explanation of different kinds of flexibility in scheduling problems as well as the systematic classification of scheduling problems. In particular, we classify the problem class discussed in the remainder of this thesis and specify its flexibility. As the third main area covered in this work, we explain the most basic principles of Petri nets, which are the modeling formalism used to derive a mathematical representation of scheduling problems. The last research domain related to this thesis is MPC. Here we focus on the most basic theoretical concepts of MPC for linear discrete time systems, which prove to be sufficient for the developed results.

Chapter 3 - Modeling of the Flexible Manufacturing System

In this chapter, we introduce the modeling and control framework that is developed in this thesis and formulate algorithms which allow to automatically generate mathematical models for the investigated class of scheduling problems. The objective of this chapter is to show how the creation of a mathematical model of an FMS and its model based control can be united in a common framework, in order to provide an integrated control engineering process.

The proposed framework builds upon on a simple formulation of the scheduling problem for an FMS and employs specifically developed algorithms to automate the generation of a mathematical model, which is the basis for the reactive scheduling by means of MPC. Consequently, it spans the whole range from system description until the model based control of the manufacturing system. As a starting point of the framework, we introduce a novel representation of a general scheduling problem. It is adjusted to the production of individual goods in Industry 4.0 by exploiting the modularity of a skill-based engineering setup through introducing a linking element between machines and products. Through its general nature it is able to represent most of the common production scheduling problems.

The automatic generation of a mathematical model for the provided problem description reduces the engineering effort for the application of the control framework. It exploits the modular structure of the description of the scheduling problem and leads to a linear discrete time model suited for the application of MPC. In order to formulate the model generation algorithms, we introduce an extension of the PN formalism, which allows to decouple autonomous evolutions of the system from conscious production decisions. We show that the PN model reflects the important characteristics of the scheduling problem. In particular, it provides the required flexibilities to represent Industry 4.0 scheduling problems based on the assumption of skill-based engineering. At the same time, the state space representation of the PN exhibits important properties for the scheduling of the manufacturing system by means of MPC.

In summary, the main contributions of this chapter are:

- The development of a framework that unites modeling and reactive scheduling.
- The formulation of the scheduling problem for an FMS in a modular way considering the principles of skill-based engineering.
- The proposition of automatic model generation algorithms that reduce the engineering effort.
- The introduction of an intuitive extension of the PN formalism to separate autonomous processes from conscious decisions.
- The investigation of the resulting mathematical model that captures the properties of the problem description and has a state space representation suited for MPC.

Chapter 4 - Model Predictive Control for Production Scheduling

In this chapter, we develop two MPC schemes for the reactive scheduling of an FMS based on the model created in Chapter 3. The objective is to provide reactive scheduling schemes which are rigorously guaranteed to complete the scheduling problem in closed loop, incorporate the economic goal of the underlying manufacturing system and are able to react to changes in the system during runtime.

At first, we formulate an intuitive MPC scheme for the scheduling of the FMS based on the PN model. Due to the automatic generation of the model from the description of a production scheduling problem, it results in an economic MPC problem without predefined mode of operation. Its recursive feasibility is proven based on the properties that the model exhibits as a consequence of the automatic generation. For providing the guaranteed completion of the scheduling problem, we exploit the modular structure of the scheduling problem, which is conserved in its PN model. We first prove the completion of the smallest modules and infer the completion of the composite elements from the completion of all its parts until the entire production problem is guaranteed to be completed. Based on the insights from the analysis of the first MPC formulation, we formulate a slightly more advanced MPC scheme, which is computationally more efficient.

For both MPC schemes, we conjointly show how changes in the manufacturing system are handled through the feedback mechanism in the control loop or by exploiting the automated modeling framework developed in Chapter 3. We discuss the relationship between the cost function employed in the MPC problem, the elements of the PN and the elements of the original formulation of the scheduling problem. In particular, we highlight how the economic motivation of the scheduling problem can be respected while providing the completion guarantees. For the case of a linear cost function, we deduce simplifications in the computations required to provide the guarantees based on the previously given proofs. Finally, we show how existing techniques to guarantee the completion of the scheduling problem can be applied to the particular reactive scheduling formulation.

In summary, the main contributions of this chapter are:

- The presentation of two MPC schemes for the reactive scheduling of FMSs.
- Providing guarantees for the completion of the scheduling problem with the developed MPC schemes.
- The possibility of the MPC schemes to pursue the economic goal of the manufacturing system while guaranteeing its completion.
- The deduction of a simplified analysis for providing the guarantees in the case of a linear cost function.

Chapter 5 - Numerical Examples

In this chapter, we employ the computationally more efficient MPC scheme proposed in Chapter 4 for the simulation of two exemplary scheduling problems from literature. The objective is to show how the MPC scheme can be used to solve scheduling problems that exhibit the characteristics of the problem class introduced in Chapter 3. We demonstrate that the proposed reactive scheduling scheme is computationally efficient, completes the scheduling problem and is able to react to changes in the system that occur during execution.

Chapter 6 - Conclusion

In this chapter, we summarize the results provided in this thesis, discuss their advantages and limitations, and give an outlook on possible future work. We emphasize the requirements for the manufacturing system to meet the assumptions made in the description of the scheduling problem. We particularly stress how further extensions can be included in the proposed framework. Finally, we point out possible connections to further results from the literature on PNs and MPC that can be exploited to extend the results developed in this thesis.

Appendix A - Proof of the Properties of the Automatically Generated Petri Net

The appendix contains the technical proof of the properties of the PN model resulting from the automatic model generation algorithms.

Chapter 2

Background and Preliminaries

The results in this thesis are based on fundamental concepts and results in production scheduling, modeling with Petri nets (PNs) and model predictive control (MPC). Therefore we briefly introduce them as preliminaries on which the rest of the thesis builds upon. Since many modeling and design choices of the developed framework are motivated by fundamental concepts in Industry 4.0, we start introducing them in Section 2.1, before presenting the fundamental preliminaries required for the rest of the thesis in the following sections. While the concepts of Industry 4.0 are explained to provide a comprehensive overview of the state of the art and ongoing developments, the further sections introduce well established terms and definitions. We start with a definition of the main terms from production scheduling that are relevant to this work and explain their dependencies in Section 2.2. In Section 2.3 we introduce Petri nets as the modeling tool that we use to represent the scheduling problem. We end in Section 2.4 with an introduction of the basics of MPC being the control concept employed for production scheduling. Parts of this section are based on and taken in parts literally from [88].

2.1 Concepts from Industry 4.0

The term "Industry 4.0" emerged as a paradigm in industrial production in 2013, when a dedicated working group in Germany presented a report in which they carved out the recent and anticipated changes in industry, economy and society [39]. Among other concepts, self-organized production systems were proposed, for which intelligent organization of assets and efficient communication between them are central aspects to achieve flexibility. To this end, the concept of *digital twin* was introduced and the *skill-based engineering* is being developed as a way to assign tasks to manufacturing units with ease. In this section, we will briefly introduce the core aspect of those concepts, which will be exploited in the formulation of the scheduling problem in Chapter 3.2 and the model creation in Chapter 3.3.

Digital Twin

We take the concept of the digital twin as proposed by Grieves [27] as the basic principle to develop the MPC framework for production scheduling. It describes the notion of having a real-time synchronized virtual equivalent of the real world objects in a digital environment that can be used in various ways, for example for hardware-in-the-loop simulations or in decision-making processes [8, 27, 36, 61]. Assuming the existence of a digital twin means to assume that the required information of every physical system is always available in the corresponding digital twin and therefore can be used for the digital control of the manufacturing system. Production systems having such a digital representation and the capability to interact with their physical environment as well as with a digital control system and among one another by means of digital communication are called cyber-physical production systems [70]. The organization of the production, the manufacturing units, and the parts being produced is coordinated digitally by means of their digital twins, which comprises their current statuses, their abilities, and a digital documentation of their past. Starting from a model-based digital twin, it is enriched with data during its lifetime in order to increase its accuracy [36]. The up-to-date status information and the knowledge about the capabilities of the physical system represented in its digital twin allow for digital panning and control and is the prerequisite to formulate the online optimization problem introduced in Chapter 4. For a manufacturing unit, the digital twin particularly holds the information on manufacturing skills it can perform in the sense of skill-based engineering. This information needs to be provided to the control system, which can be done in the form of a digital directory as for example the "yellow pages for Industry 4.0" [44]. Such a digital directory serves as an organizational interface that allows to exploit the modularity and flexibility in the manufacturing system. Besides the digital twins of the manufacturing units, a digital twin is initialized for every customer specific order that is placed at the manufacturing system. From the digital twin of the products, especially the required steps for their production are of interest for our approach. As a result, the assignment between orders and manufacturing units is done based on their digital twins.

Skill-Based Engineering

A promising approach to exploit the information provided in the digital twins is the concept of skill-based engineering, where capabilities of a manufacturing unit are abstracted to a higher level [17, 54]. On this abstraction level, the production system is represented in a modular fashion, in which the hardware and software functionalities are represented as distinct modules that offer specific skills and can be flexibly interconnected [23]. The products to be manufactured are also designed in a modular way and require certain skills for being produced. A matching between required skills for the production of a product and assured skills, which are provided by the machines, is performed. This concept can be seen as a variation and a further development of service-oriented automation, which is based on the concept of software services that allow flexible interconnection between software modules [62]. The formulation of the instructions to manufacture a product is focused on the workpiece that is being created, in the sense that it describes what to achieve with the workpiece but not the exact process required to achieve the goal [5]. Skill-based engineering uses the modularization of production processes in the form of skills as a means to facilitate process planning and automation in order to make it more flexible [69]. Due to its modularity, the single components in a skill-based architecture can be exchanged without losing functionality or requiring complex adaptions [17]. On the high abstraction level, the operator or the control software can access the skills of the machines and give the desired instructions, which are passed to the machines that interpret and execute the incoming commands according to their capabilities by means of a subordinate logic. This approach enables the flexible use of versatile manufacturing units in complex production scenarios. The goal of the scheduling scheme proposed in this thesis is to appropriately match the required skills and the assured skills on the higher abstraction level. On this level, the same task or skill might be implemented differently on different types of machines. For example, the tightening of a screw can be done with a tool that can rotate infinitely, or with a robotic arm that can only rotate by a limited angle and therefore needs to turn back and forth several times. Both implementations solve the same task and lead to the same result and therefore can be seen as the same skill, but both having different parameters in particular with respect to speed. In general, we consider the skill to execute a task in an abstract and universal way. For the problem formulation, which we will provide in Section 3.2, the skills are the central element for the assignment between jobs and manufacturing units. The proposed scheduling framework is an approach to systematically automate this assignment process.

2.2 Production Scheduling

As a brief introduction to the field of production scheduling, we first introduce the most important terms for the remainder of this thesis and explain their meaning. After that, in the scope of scheduling of flexible manufacturing systems (FMSs) in an Industry 4.0 context, we provide a more detailed overview on different types and notions of flexibility in the production scheduling context. In the last part of this section, we discuss a scheme from literature that is used to classify scheduling problems and classify the problem considered in the remainder of this thesis with respect to this scheme.

The process of *production scheduling* is the assignment of the operations, which have to be executed in a production system, to the available resources and a corresponding starting time with the goal to optimize one or more objectives [6, 31, 66]. The result of production scheduling is a *schedule*, which is an assignment of operations to machines and a starting time [6]. These definitions rely on the terms production system, operation and resource, which have to be defined in this particular context.