Universität Potsdam
Univ.-Prof. Dr.-Ing. habil. Norbert Gronau
Lehrstuhl für Wirtschaftsinformatik,
insb. Prozesse und Systeme
Universität Potsdam
August-Bebel-Str. 89; 14482 Potsdam
Tel. ++49 331/ 977-3322, Fax -3406
http://wi.uni-potsdam.de
E-Mail: ngronau@wi.uni-potsdam.de

Work Report WI - 2016 - 02

Grum, Marcus; Dehnert, Maik;
Vollmer, Frederic; Zhao Mingxian

The Conception of a Cyber-Physical Market Model as Coordination Instrument for Production Systems

Zitierhinweis: Grum, M., Dehnert, M., Vollmer, F., & Zhao, M. (2016). The Conception of a Cyber-Physical Market Model as Coordination Instrument for Production Systems. In Work Report WI - 2016 - 02, First Edition, September 2016

Abstract

As traditional production components are considered as cyber-physical systems (CPS), they become intelligent and decide for themselves. Interacting within a cyber-physical production system (CPPS), each is following individual objectives and a coordination framework for the entire production context is needed w.r.t. the company's global objectives. In accordance to real market applications, the following project introduces a concept for a cyber-physical market (CPM). This considers each CPS as market participant having an individual demand and supply such that well known market mechanisms serve to coordinate and optimize the entire CPPS.

Kurzdarstellung

Sofern klassische Produktionskomponenten als cyberphysische Systeme (CPS) betrachtet werden, können sie ihre Intelligenz und Fähigkeiten steigern und eigenständige Entscheidungen treffen. Im Verbund als cyberphysisches Produktionssystem (CPPS) folgt jedes einzelne individuellen Zielen, sodass ein Koordinationssystem für den gemeinsamen Produktionskontext erforderlich wird, welches individuelle lokale Ziele mit globalen Produktions- und Unternehmenszielen in Einklang bring. In Anlehnung an reale Marktanwendungen konzeptioniert das vorliegende Projekt einen cyberphysischen Markt (CPM), welcher jedes CPS als Marktteilnehmer mit eigenem Angebot und eigener Nachfrage interpretiert, sodass bewährte Marktmechanismen das CPPS koordinieren und optimieren.

Table of Contents

List of Figures

List of Tables

List of Formulas

List of Abbreviations

AZI	Anwendungszentrum Industrie 4.0
C	Conveyor
CPM	Cyber-Physical Market
CPMP	Cyber-Physical Marketplace
CPS	Cyber-Physical System
CPPS	Cyber-Physical Production System
CPPSB	Cyber-Physical Production System Bank
D	Demand Curve
DSRM	Design Science Research Methodology
H	Human
M	Machine
P	Prices
Q	Quantity
S	Supply Curve
WP	Workpiece

1. Introduction

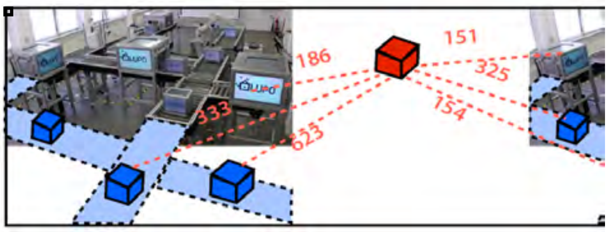
Simple production components become intelligent and decide for themselves. Figure 1 (a) shows how those can be enhanced to CPS, which is visualized by the mapping of Figure 8 to selected machines. Typically, the complexity of the non-transparent operations in application center for Industry 4.0 (AZI) hampers the understanding by investors. A lack of autonomous coordination possibilities, the dictates of programmed sequences and ERP systems and the lack of a simulation environment makes collecting data and testing of processes complex and time-consuming.

Based on the idea to create a cyber-physical pendant in similarity to real markets in order to support and realize those decisions, within a series of projects, a cyber-physical market is realized under lead of Marcus Grum. The assumption: Through an exchange of supply and demand of each individual CPS, the entire cyber-physical production system (CPPS) can coordinate itself autonomously and run optimized. Within this first project, the aim is focused on the creation of a concept of such a cyber-physical market (CPM). The creation of a virtual market supports the transparency and enables intuitive understanding of operations. All, the creation of a CPM as a coordination ability for autonomous systems (first project), the simulation environment for testing processes (second project) and the visualization of non-transparent complex processes (third project) could enable the full potential of autonomous systems within the CPPS. This vision is visualized in Figure 1 (b), which shows the CPM within the AZI with augmented reality elements e.g. through AR-glasses. Here, one can see real elements of the AZI, which is virtually extended (blue color). Further, one can see the CPM and its information exchange (red color).

Thus, the research in this first project deals with the question, what issues can be addressed by putting market principles on a cyber-physical production environment. Other derived research questions deal with how to design market interaction mechanisms in cyber-physical systems, i.e. by negotiations, for coordination within system components that act as market participants, based on real-world markets. Therefore, we will extend the research approach by Gronau et al. (2015) with cyber-physical market's demand and supply curves for autonomous self-organization in cyber-physical systems. Further, we discuss several issues to be solved in a self-organizing production scenario by CPMs. Finally, we cope with several questions in an extended outlook: What new paradigms can we use i.e. for scheduling, internal pricing, adapting to change by environmental disturbances?

The respective fields of research deal with adaptability and mutability of production systems, which are derived from and later implemented in the AZI, related to state-of-the-art practices, which are partly apprehended, and developed further in this work.

(a) Components of AZI 4.0 interpreted as CPS



(b) Visualization of the cyber-physical market model

Figure 1: Strategic project goal for AZI 4.0 (own illustration)

The work is structured in the following way: The second part introduces theoretical foundations. The third and main part deals with the conception of the CPM. It describes the assumed production scenario, introduces assumptions for market mechanisms and describes the derived negotiation algorithm in detail. The fourth part describes further steps to go for practical implementation of the proposed CPM and recommends the realization based on an agent-based programming. The fifth chapter concludes the work with a summary and an extended outlook for further research.

2. Theoretical Foundations

2.1 Methodology

Methods in Business Informatics can be divided into design research methods: "How are artifacts designed and evaluated" and artifact construction methods: "What are concrete, specific for the solution of problems related to information systems, to make and evaluate artifacts" (Gericke and Winter, 2009). Examples of appropriate research results are software prototypes, conceptual (reference) models, modelling languages, methods or conceptual frameworks (Frank, 2000). Thus, a construction-based methodology for the design of the artifacts was used. An artifact must both contribute to practical problem solving as well as to gain knowledge in science. Design science research requires the creation of an innovative, purposeful artifact for a special problem domain. The artifact must be evaluated in order to ensure its utility for the specified problem. In order to form a novel research contribution, the artifact must either solve a problem that has not yet been solved, or provide a more effective solution. Both the construction and evaluation of the artifact must be done rigorously, and the results of the research presented effectively both to technology-oriented and management-oriented audiences (March and Storey, 2008).

Our research faces the creation of a cyber-physical market in a production environment. It follows Gronau et al. (2015). Thus, the research agenda of this project is divided in various steps as can be seen in Figure 2. As an initialization step, the foundations were set following a systematic approach, the research question was formulated. Requirements for the CPPS, the approach and the model were given (c.f. Gronau et al., 2015). Further, the production elements were introduced (machines, workpieces etc). Within step 1, an appropriate understanding of autonomy was defined. For the determination of the optimal degree of autonomy an underlying model needs to be specified, which is filled with qualitative assumptions and hypotheses. In particular, the model definition is starting point of this work. In the next step, based on those definitions, the CPM is built and realized, which is the main part of this paper that introduces the CPM concept and the negotiation algorithm design.

In a third step, the validation of the model will take place. Real tests within a CPPS environment will be realized. With this step, the research cycle is closed and further iterations can be realized on a greater level of detail such that refinements can be realized, the knowledge base can be extended iteration by iteration and further influence factors can be considered as well (Gronau et al., 2015).

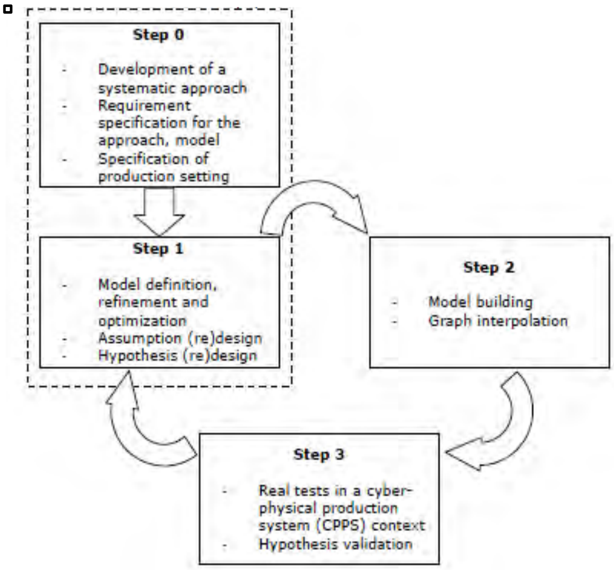


Figure 2: LSWI Research Cycle for CPPS Optimization (Gronau et al., 2015)

For this purpose, we use the Design Science Research Methodology (DSRM, Peffers et al. 2007) as research approach. DSRM incorporates principles, practices and procedures required to carry out research. It is chosen as it meets several objectives of Design Science artifact construction:

- consistency with prior literature,
- nominal process model for doing DS research,
- a mental model for presenting and evaluating DS research (Peffers et al. 2007).

The process includes six steps: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication. Steps in development of algorithms then are: Problem definition, development of a model, specification of algorithm, designing an algorithm, checking the correctness of algorithm, analysis of algorithm, implementation of algorithm, testing, documentation. During the project, we focused on first three steps (problem definition, development of a model, specification of algorithm, designing an algorithm). Later projects should begin by checking correctness of the algorithm design through implementation and testing (step 3 in LSWI research cycle).

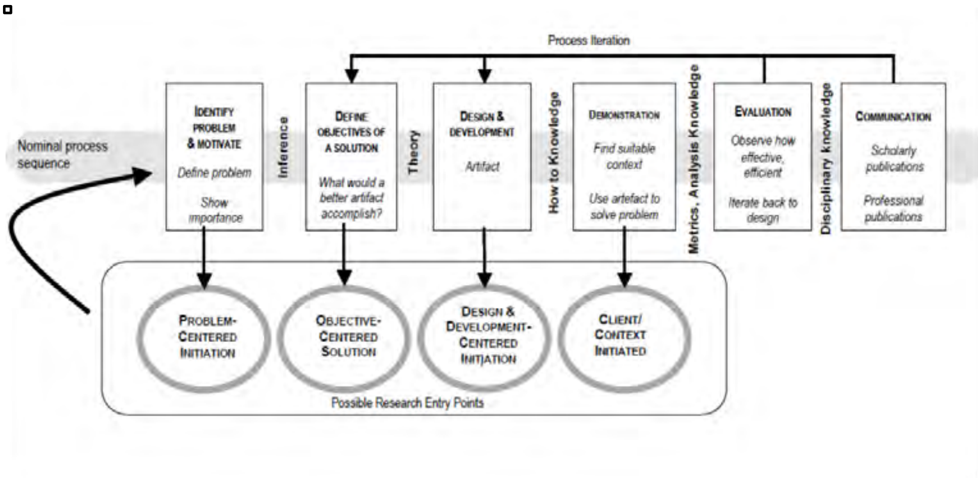


Figure 3: Design Science Research Methodology (Peffers et al. 2007)

2.2 Economics

Microeconomics aims to explain how price allocates the resources and regulates the economy, hence the price is the central theory of microeconomics. The market price is determined by the relationship between supply and demand, so the determined theory of supply, demand and price has become the starting point of project-relevant microeconomic theory. This section firstly defines a market, then analyzes the general principles of demand and supply, and based on built foundations, it describes how to determine equilibrium price under the conditions of a competitive market, in order to give some applied principles in the project.

2.2.1 Market definition

A market refers to the "economic place of supply and demand, on which pricing and exchange perform" (Woll et al. 2000, p.496). The market is thus characterized by three essential defining characteristics (Schwickert und Pfeiffer 2000):

1. First, a market is an institution, an abstract control system for market participants.
2. Second, a market is constituted in the market transaction with the characteristic phases: information / selection, arrangement, processing and optionally post contracting phase. Unlike the transaction in hierarchies the market transaction is based on the principle of spontaneous contracting between autonomous market participants.
3. Third, a market is considered as a functional mechanism for the formation of prices, using the instrument of coordination of market participants. Contrary to this, a marketplace is a real place for encounters of market participants.

A marketplace therefore represents the infrastructure for market events. Market events are organized according to fixed rules in the market, where a definable circle of market participants comes together to prepare and carry out a transaction. Most often, this is done at the initiative of a marketplace operator, who can also be market participant itself (Picot et al. 2003).

The perfect market is designated with rational behavior and utility maximization and thus comprises (Cezanne 2005):

- There are neither personal (for example, through advertising), temporal (e.g. opening times) and objective (for example, volume discounts, service differences) nor spatial preferences.
- There is full market transparency.
- Uniformity (standardized quality / equality) of the goods.
- Immediate response: All market participants react immediately to changes in market variables.

Those definitions serve in the following as basic definitions and will be mapped to the cyber-physical context.

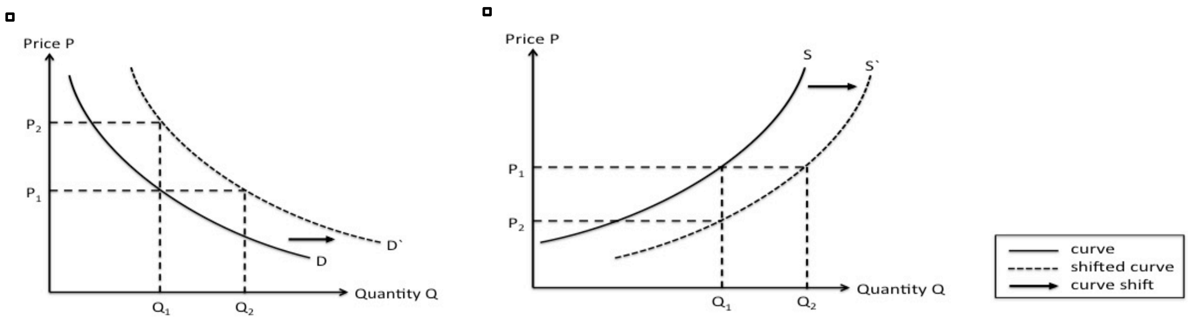
2.2.2 Demand and supply

Demand and supply is perhaps one of the most fundamental concept of economics and it is the backbone of a market economy. Hence, in the last decades, various explanations and works have been published within this domain. The following basic explanations refer to (Pindyck und Rubinfeld 2009):

Demand refers to the choice-making behavior of consumers. The demand curve shows how much of a good consumers wish to buy at a certain unit price. This relationship between the quantity demanded and the price can be represented graphically as in Figure 4 (a) focusing the designated demand curve D. It should be noted that this curve is downward sloping: Usually, consumers are willing to buy more if the price is lower. But this effect decreases because of the elasticity (see chapter 2.2.3). For example, a lower price encourages consumers to consume larger amounts. Similarly, this may bring other consumers that could not afford the goods before to buy it now. Of course, the amount of a good that consumers want to buy also depends on other factors in addition to the price. The income is particularly important. Higher budgets could lead consumers to spend more money for goods if demanded.

We examine what happens to the demand curve, if income levels increase. As shown in Figure 4 (a), an increase in the quantity demanded is expected if the market price remains constant at P_1 - for example, from Q_1 to Q_2. Since this increase would occur regardless of the market price, the result would be a shift of the entire demand curve to the right. In the figure, this is represented as a displacement of D to D'. With higher incomes, they should be willing to pay a higher price - for example, in Figure 4 (a), this is P_2 instead of P_1. Here, again, the demand curve shifts to the right. The term *change in demand* is used for shifts in the demand curve, while term *change in the quantity demanded* is used for movements along the demand curve.

The supply curve represents the amount of a good that producers want to sell at a certain price, keeping all other factors that may affect the quantity supplied constant. This is illustrated by the marked S curve in Figure 4 (b). The vertical axis of the graph indicates the price P of a commodity measured in money per unit. It is the price the seller gets for a certain quantity offered. The horizontal axis represents the total offered amount Q measured in number of units per period. Therefore, the supply curve shows the relationship between the amount offered and the price. Thus, the higher the price, the more willing supplier machines are to offer and sell their services. The offered amount can, in addition to price, also depend on other variables. For example, the amount depends not only on the achieved price but also on their production costs, including wages and salaries, the interest charges and the cost of raw materials. We have pointed out that the reaction of the offered quantity to price changes can be represented by movements along the supply curve. The term *change in supply* is used for shifts in the supply curve, while term *change in the quantity supplied* is used for movements along the supply curve.



(a) Demand curve shift *(b) Supply curve shift*

Figure 4: Demand and supply curve (Pindyck und Rubinfeld 2009)

The two curves intersect at the point of equilibrium or market clearing price and the corresponding quantity. At this price (P^*_1 in Figure 5), the quantity supplied and the quantity demanded is exactly the same (in Q^*_1). The market mechanism in a free market tends to alter the price until the market is cleared, which means that the quantity demanded and offered are equal.

Since there is neither excess in demand nor an excess of supply, there is no pressure for further price changes at this point. Equilibrium is the point of balance between demand and supply in the market.

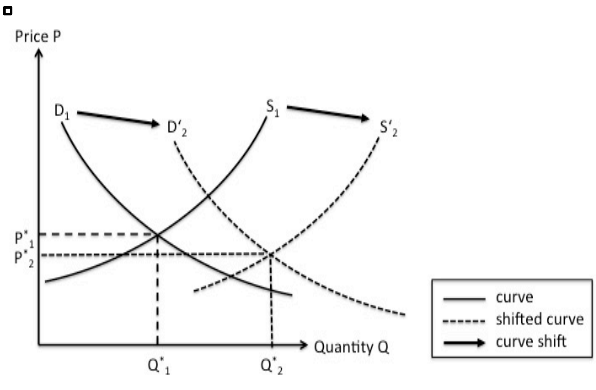


Figure 5: Demand and supply equilibrium (own illustration)

Considering Figure 5, curve shifts of the demand and the supply curve can occur simultaneously. When demand or supply curve changes, there will be a new equilibrium in the next time step, which here is Q^*_2 and P^*_2. In general, when D = S, the price is the equilibrium price and the quantity is the equilibrium quantity, which is shown by the asterisk character.

2.2.3 Elasticity

The elasticity measures the sensitivity of a variable with respect to another. In particular, it involves a number indicating the percentage change that occurs at a variable in response to a change in another variable by one percent. For example, the price elasticity measures the elasticity of demand - the sensitivity of quantity demanded with respect to price changes.

$$Elasticity = \frac{\%\ change\ in\ quantity}{\%\ change\ in\ price} \tag{1}$$

Formula 1: Elasticity with respect to prices

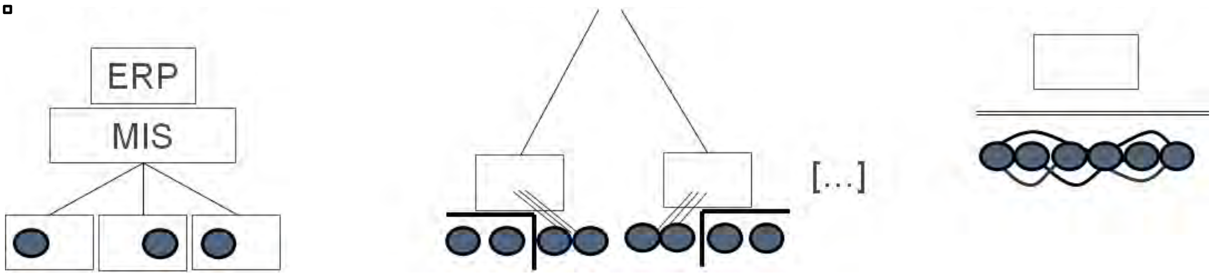
Changing elasticities have been considered within the previously shown figures since the demand and supply curves are non-linear and their slope changes.
As Gronau et al. (2015) indicate, the elasticity of the supply decreases by increasing the degree of autonomy, but the elasticity of the demand increases by increasing degree of autonomy in our production scenario. This is a statement that can be validated with help of the CPM.

2.2.4 Degree of Autonomy (DoA)

According to Collins Dictionary (Brookes 2014), autonomy describes either:

1. the right or state of self-government,
2. a state, community, or individual possessing autonomy,
3. freedom to determine one's own actions, behavior, etc.,
4. a) the doctrine that the individual human will is or ought to be governed only by its own principles and laws or b) the state in which one's actions are autonomous.

Following these ideas within the more economical context of our production scenario, degree of autonomy is a measure for (in-)dependency on hierarchical structures in decision making within the CPS. The higher the degree of autonomy is, the higher is the level of independence of a CPS in its decision freedom. Thus, it is defined on a continuous scale between 0 and 1 leading to different assumptions of system behavior that describe how centrally (DOA=0) or autonomously (DOA=1) the CPS is organized from its point of view within the CPPS (c.f. Figure 6).



(a) heteronomy (DoA = =) *(b) interim continuum (0 < DoA < 1)* *(c) autonomy (DoA = 1)*

Figure 6: Degree of Autonomy (DoA) representation (own illustration)

- DoA equal 0 describes very rigid systems, meaning i.e. a workpiece to be very inelastic w.r.t. prices, time per order or further optimization dimensions, having the tendency to pay very high prices, bad time per order or further non-optimal relations for making contracts due to lack of decision freedom and high heteronomy.
- 0 < DoA < 1 describes transitional states in between rigidity and flexibility whose concrete computational design is still subject to research (c.f. outlook) as many designs are conceivable.
- DoA equal 1 assumes most flexible systems, meaning i.e. a workpiece having a lot of freedom of action (very elastic) due to a very high decision freedom and less heteronomy. Here, it shows elasticity w.r.t. prices, time per order relations or further dimensions.

Within this project, a CPM is conceptualized that intends to realize a Pareto optimal situation. Hence, the result has to be situated in the DoA representation (b) within Figure 6. Since all market participants are intended to stand on an equal footing, we define the initial position of the CPPS at DoA = 0.5, which changes as the position of a single CPS is preferred, the single elasticities distinguish, groups of representatives are identified, etc.
The simulation approach of the third step of the LSWI research cycle is promising to capture results and conclusions from the prototype including various degrees of autonomy. Hence, drawbacks w.r.t. the assumed optimum can be found, which is visualized in Figure 7.

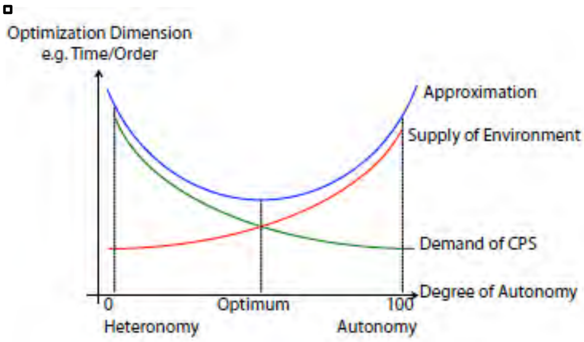


Figure 7: Supply and demand of each CPS (Gronau et al., 2015)

In parallel to Formula (1), which is the elasticity w.r.t. prices, the elasticity w.r.t. DoA is the degree to which the demand curve of a CPS or the supply curve of its corresponding environment reacts to a change in DoA (Gronau et al., 2015):

$$Elasticity = \frac{\%\ change\ in\ DoA}{\%\ change\ in\ optimization\ dimension} \tag{2}$$

Formula 2: Elasticity with respect to DoA

Focusing on the elasticity w.r.t. DoA, the CPM is intended to be an evaluation framework for the assumptions in Gronau et al. (2015).

2.3 Cyber-physical systems and cyber-physical production systems

Cyber-physical systems are "systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the internet" (Monostori 2014). Cyber-physical production systems are strongly related to Industry 4.0.

Following Gronau et al. (2015), CPSs consist of physical production components enhanced by embedded systems connected to the internet of things, collaborating to control, connected by using internet protocols. Sensors, actuators and processors are defining a loop of perception, processing and interaction of the CPS and its environment (see Figure 8).
Communicator components can serve to let CPS communicate with its environment, such that a negotiation can be carried out.
As we will discuss in the outlook of this paper, different kinds of decision strategies can be implemented in a CPPS. Single CPSs are able to follow their strategy autonomously.

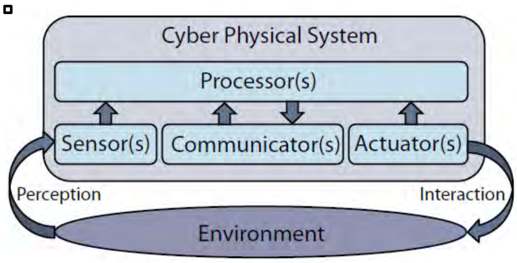
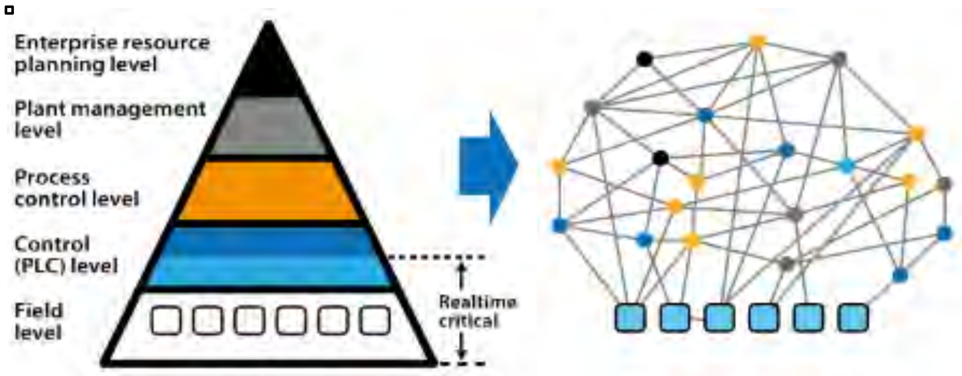


Figure 8: Schematic structure of cyber-physical systems (Gronau et al., 2015)

Monostori further specifies CPPS to consist of autonomous, cooperative elements and subsystems (Monostori 2014). Those are getting into connection with each other in situation dependent ways:
As Figure 9 visualizes, they are getting into connection on and across all levels of production, from processes through machines up to production and logistics networks. In this figure, on the leften side, one can see the automation hierarchy of traditional production systems using different colors and shades. Each has different requirements, relations to real time criticalness and lower levels are overruled by higher hierarchy elements. On the righten side, one can see the CPS-based automation using the same colors. Since CPS are enabled to decide autonomously, the pyramid level is broken up and the CPS can be found in a network similar structure. Following Monostori, the fundamental question here is to explore the relations of autonomy, cooperation, optimization and responsiveness.



(a) Automation hierarchy *(b) CPS-based automation*

Figure 9. Decomposition of the automation hierarchy (Monostori 2014)

In this project, all CPS are considered as fully meshed components within an internet similar structure following Gronau et al. 2015, such that an efficient market can be placed within the CPPS.

2.4 Flexibility, adaptability and mutability

Dynamic adaptability of systems due to environmental disturbances is necessary due to several constantly changing, volatile factors: economy, staff, social and political factors, customers, competition, products and technologies (Gronau, 2006). Mutability is the ability of a system to adapt efficiently and quickly to these changing requirements in a self-reliant manner. In contrast to flexibility, the system itself recognizes the need for change and develops suitable alternatives (c.f. Table 1). This capability of a (cyber-physical) system is achieved by the CPM approach as the whole CPPS consists of self-adapting CPS by means of market transactions. The marketplace just sets the overall frame for the whole system to self-regulate.

Pattern	**Who recognizes the need for change?**	**Who develops suitable alternatives?**
Flexibility	external	external
Adaptability	internal (system)	external
Mutability	internal (system)	internal (system)

Table 1: Comparison of flexibility, adaptability, mutability (Gronau 2006, p.37)

Self-organization is an important concept of autonomic computing to self-manage systems in self-optimization. Mutability comprises by several factors (c.f. Gronau 2006, p.37):

- self-similarity (different structure on different layers),
- knowledge (self-disclosure of the system),
- interoperability (means of communication with other systems),
- scalability (bidirectional capacity-adaption),
- modularity (independent evolution of structures),
- availability (access independent of time and space),
- independence (autonomy of subsystems),
- self-organization (structure-building system capabilities).

In this work, we assume that markets can efficiently support the described requirements of mutability. As they are well studied in other contexts but have not yet been applied to a certain production context in research and practice, we will introduce a cyber-physical market concept for autonomous cyber-physical systems within the third section.

2.5 Literature review

A systematic literature review has been carried out in order to conquer thematic intersections. In the following, search terms have been highlighted. The introduced concepts will be summarized in Table 2 in an author-centric manner. State of the art literature on autonomous production systems such as cyber-physical systems (CPS) or cyber-physical production systems (CPPS) can be separated into theoretical contributions and more practical implementation proposals i.e. by means of agent-based systems.

Theoretical contributions focus on several research areas in production such as **cyber-physical systems**, **adaptability** and **autonomy**:

- Keddis et al. (2013) observe decreasing life cycles of many products and increasing number of variants of one product. Adaptable manufacturing systems can cope with these requirements. Thus, they focus on adaptability and propose a model-based approach, based on system capabilities, setup of the factory and the production plans.
- The capability-based planning approach is then further developed further by Keddis et al. (2014) to ensure flexible responses to changes in markets by adapting products, product variants, and product volumes. To support such variety in products, the authors suggest a capability-based approach for production planning and scheduling. Further, production plans and machines are described in terms of required capabilities (Keddis et al. 2014, p.1). The approach generates a valid schedule for the currently available machines in the factory according to the production plans.
- Klöpper et al. (2012) focus on scheduling for evolving manufacturing systems. Evolving manufacturing creates complex systems of objectives in manufacturing control. To meet the challenges of flexibility, they developed a scheduling framework that supports alternative process plans and considers the internal states trajectories of resources. In order to support the user in a complex decision-making environment, evolutionary multi-objective optimization is used to generate a set of relevant schedules. Further, Klöpper et al. (2014) exploit new paradigms for designing manufacturing systems such as adaptive and service-oriented manufacturing systems or self-optimizing resources. This contribution considers alternative resources and introduces a multi-objective scheduling concept based on evolutionary algorithms and Hierarchical Precedence Graphs.
- Gronau et al. (2015) research on production systems that are enhanced by cyber-physical systems and Internet of Things. Those cyber-physical production systems are able to raise the level of autonomy of its production components (Gronau et al., 2015). The research approach by the authors is proposing a simulation concept. Based on requirements and assumptions, a cyber-physical market is modelled and qualitative hypotheses are formulated. Our work mainly uses this approach to design the virtual market in the given context as described in section 3.1.

- Theuer et al. (2013) describe the effects of the usage of autonomy for a decentralized production control and benefits for various objectives that can be classified. The paper introduces a three-layer cluster for the classification of the level of autonomy.

Several papers cope with the practical implementation of (virtual) markets by means of **agent-based programming** approach:

- Tsvetovatyy et al. (1997) describe an architecture for an agent-based virtual market that includes all elements required for simulating a real market such as infrastructure for communication, mechanisms for storage and transfer of goods, banking and monetary transactions, and economic mechanisms for direct or brokered producer-consumer transactions (Tsvetovatyy et al. 1997).
- Collins et al. (1998) present a generalized market architecture that provides support for complex multi-agent contract negotiations. They present a negotiation protocol for planning by contracting that takes advantage of the services of the market.
- Ha (2010) describes interactive negotiation for agent-based decision making in the electronic marketplace with a possibility to select different negotiation strategies.
- Sahin et al. (2015) propose a multi-agent-based system for scheduling of flexible machine groups and material handling system in a dynamic manufacturing environment. The agents in the model are autonomous as they cooperate and negotiate with other agents in the system.
- Esmahi et al. (2000) propose on an open virtual marketplace where agents process their marketing transactions. Thus, their introduced model supports a variety of transactions types, from simple buying and selling to complex multi-agent contract negotiations, mediating in case of negotiation conflicts.
- Another agent-based negotiation approach is proposed by Wong et al. (2006) who integrate process planning and scheduling. A multi-agent negotiation protocol is introduced for effectively coordinating the interactions between the part agents and the machine agents.
- Lau (2007) introduces a web services and intelligent agent-based negotiation system for B2B applications.
- Al-Sakran (2014) describe the application of intelligent agent in negotiation between buyer and seller in B2C commerce using big data analytics.
- Finally, more in general the textbooks by Fasli (2007) and Wooldridge (2009) explain the main theory and the applications of agents, serving as a compendium for transaction design i.e. by negotiation or auctions.

The system elements have been partly derived using general process phases of electronic service marketplaces (e.g. described by Schenkel, 2015):

- Schenkel uses a Design Science Business Engineering approach to develop and evaluate a generic marketplace for electronic services. Next to functional and nonfunctional system requirements of virtual marketplaces we derived IT architecture element descriptions which will be implemented by means of Agent-based simulation and later introduced in this work.

Table 2 summarizes the literature influence on the project by concept, with a remark on what is used in particular within this work.

Concept	**Authors**	**Important aspects in our work**
CPS, CPPS	Monostori (2014); Gronau et al. (2015)	Cyber-physical system thinking, full meshed communication infrastructure
Capability-based planning	Keddis et al. (2013); Keddis et al. (2014)	Operational plans, capability lists for suitable contracting
Autonomy	Theuer et al. (2013); Gronau et al. (2015)	Degree of autonomy as an indicator for flexibility of cyber-physical systems
Scheduling	Klöpper et al. (2012); Klöpper et al. (2014)	Heuristics for scheduling
Agent-based modeling	Tsvetovatyy et al. (1997); Esmahi et al. (2000); Wong et al. (2006); Lau (2007); Ha (2010); Collins et al. (1998); Sahin et al. (2015); Al-Sakran (2014); Fasli (2007); Wooldridge (2009)	Agent-based implementation
(Virtual) Markets	Esmahi et al. (2000); Schenkel (2015); Fasli (2007)	(Virtual) marketplace design
Negotiation	Collins et al. (1997); Fasli (2007); Wooldridge (2009)	CPS interaction, demand side (workpiece) initiated contracting, offering by suppliers (machines / conveyors)

Table 2: Literature review overview (own work)

3. Conception of a cyber-physical market model

3.1 Cyber-physical market definition

Following the definitions of chapter 2.2.1, we define a cyber-physical market (CPM) to be a market, which refers to the economic place of cyber-physical supply and cyber-physical demand, on which pricing and exchange perform. Analog to (Schwickert und Pfeiffer 2000), the CPM is thus characterized by three essential defining characteristics

1. A CPM is an institution, an abstract control system for CPM participants.
2. A CPM is constituted in the market transaction with the characteristic phases: information / selection, arrangement, processing and optionally post contracting phase. Unlike the transaction in hierarchies the market transaction is based on the principle of spontaneous contracting between autonomous CPM participants.
3. A CPM is considered as a functional mechanism for the formation of prices, using the instrument of coordination of CPM participants. Contrary to this, a cyber-physical marketplace is a real place for encounters of CPM participants.

Building on (Picot et al. 2003), a cyber-physical marketplace (CPMP) therefore represents the infrastructure for CPM events. CPM events are organized according to fixed rules in the CPM, where a definable circle of CPM participants comes together to prepare and carry out a transaction. Most often, this is done at the initiative of a CPMP operator, who can also be market participant itself.

Analog to (Cezanne 2005), the perfect CPM is designated with rational behavior and utility maximization and thus comprises:

- There are neither personal (for example, through advertising), temporal (e.g. opening times) and objective (for example, volume discounts, service differences) nor spatial preferences.
- In the CPM is full market transparency.
- Uniformity (standardized quality / equality) of the goods.
- Immediate response: All CPM participants react immediately to changes in CPM variables.

The perfect market criteria are assumed to be fulfilled within a CPPS in our model according to the following assumptions taken from Gronau et al. (2015):

1. We assume a fully meshed communication infrastructure between CPS. Every CPS is able to communicate with the other CPSs in the system.
2. The determination of individual CPS optimum is an interplay of individual CPS and the environment. This defines the CPM equilibrium.
3. We are interested in the Pareto optimum for the whole CPPS.

Pareto efficiency or Pareto optimal, named after the economist and sociologist Vilfredo Pareto, is the set of states in which it is not possible to improve a property without having to simultaneously degrade another one. Here, the flexible CPPS communicates with the production stakeholders (clients, suppliers, service people etc.; c.f. section 3.2.1) in order to replace the traditional linear, hierarchical planning. The resulting solution space of the whole CPPS can be seen as one great optimization task and is not known at all in advance (Gronau et al., 2015).

3.2 Production scenario

3.2.1 Scenario framework

To have a base for reengineering specific production administration procedures, like scheduling and the related decision making process, we needed an example suitable to a real production environment. The "Anwendungszentrum Industrie 4.0" (AZI), a real-world demonstration on campus serves as example production environment since the main components to be introduced are the same for all production scenarios to be conducted.

Following the project foundations by Gronau et al. (2015), a typical production system consists of production machines (e.g. printer) and workpieces (e.g. an identifiable box with raw materials that are to be processed). Within production, machines are transforming one or more input materials in one or more output products. To connect the machinery, conveying belts are used, which ensure that the output of a former production step is transported to the next production step within the production steps.

In the following we will give brief definitions and explanations for roles in the CPMP:

- Client
    - The client asks for a certain service or good, and gives boundaries or *underlying functions* for values such as pricing, timing, quality and gets a real-time response by the system. In a near-to-reality scenario with implemented CPM functionality, a CPM client has more options and introduces requirements affecting KPIs that are more flexibly changeable than in a conventional factory. The variables stay changeable through the course of production, if the system is made with efforts regarding mutability.
- Factory owner
    - The factory owner is a profit-oriented subject hierarchically above the CPPS, that generally takes responsibility for the interaction with the clients and suppliers. Also the owner may take steps to change the production environment.
- Machine
    - A machine is a type of agent at the supply side. It is participant of the virtual market and processes workpieces and is connected by conveyors. It calculates prices, does scheduling, and uses input parameters such as properties of all agent types and external information like company-wide pricing and scheduling.
- Workpiece
    - A workpiece is a demanding type of agent. Workpieces have many properties that in the end result in different ways of production and different input parameters for calculations. A workpiece interacts with machinery to manage scheduling and to get processed in the factory environment. In our use case, it is an identifiable box with raw materials that are to be processed (e.g. paper).
- Conveyor
    - Conveyors are supply-side agents in our environment. They manage timing of transportation of workpieces and connect machinery or other conveyors.
- Queue
    - Queue lines are handling waiting times in between production steps and solve a reordering of workpieces. Workpieces that are blocking the throughput can be stored temporarily in case of a sudden change of the machine environment or a higher demand of machines on later production steps. Hence, they supply space.
- Human
    - A human worker may manually change any variables and parameters, or rearrange the production environment.
    - When developing the factory layout (see figure 10 "production scenario"), the caption human was used to display an interface, where a production step is done by human or quality is assessed by a human worker (thus their work schedule is relevant). They supply their human work force.

3.2.2 The "printing-shop" scenario

The reality-closest factory layout was a printing shop, where different machinery and workpieces are interacting to produce printing goods in different quality and size within a self-organized scenario. The printing shop was chosen because of easy comprehensibility and variability. It can handle different qualities and sizes of paper and so on, and machinery and workpieces may find different production cycles they can compare. Further, it is necessary to include parameters like speed, or variables like electricity costs, or even adapting production parameters like a changing degree of quality. Moreover, it is feasible to include parameters, distinguishing between the machine agents, such as the capability of processing an amount X of papers per minute, or the capability of printing in color, or printing on glass.

The arrangement of the machines within the CPPS can be seen in Figure 10. Here, one can see machines visualized by dark rectangles and conveyors visualized by grey rectangles. While the process starting point and ending point are visualized with help of white rectangles and serve as interface for the production process entry and outlet, human worker are visualized with help of yellow rectangles.

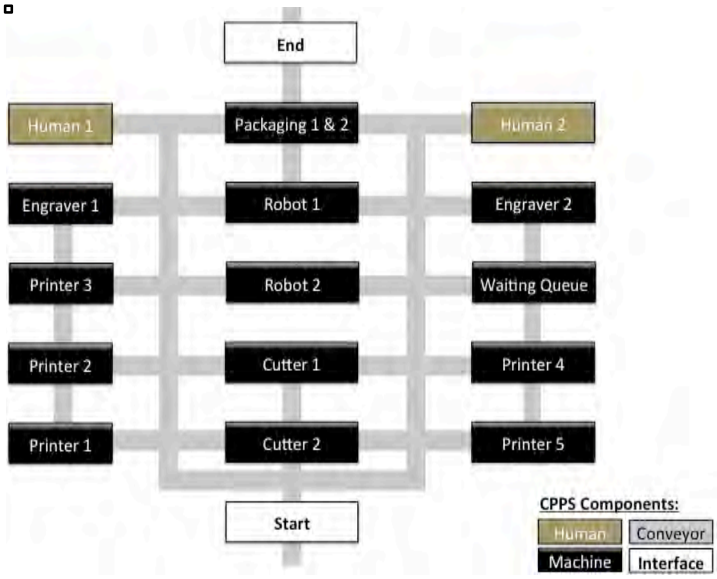


Figure 10: Production scenario (own illustration)

This design was built with the intention to consider the following points:

- a set of at least 4 machine types was to be used to produce the most complex product,
- each set of producing machine types was to consist of at least two representatives,
- a set of only one human worker type was to be used,
- each set of human worker types was to consist of at least two representatives,
- each representative was to show different attributes (production speed, quality, costs, …),
- various ways to a machine representative was to be considered,
- bottle necks were to be considered (e.g. both of the human workers only can be accessed via one conveyor route),
- space limitations was to be considered (e.g. because of building room limitations as printer 1 and printer 5 can not be accessed with conveyors coming from the bottom),
- machine limitations was to be considered (e.g. robot 1 and robot 2 can not be accessed coming from the bottom or the top.

Within this scenario, different kinds of products (from simple to complex) were to be produced. For this, three exemplary products have been focused. Each needs different parts such as frames, panels, paper, glass or metal and needs different machines to carry out the required production steps. The required production order and production parts of those three workpiece types are visualized in Figure 11.

Workpiece 1: Panels
Parts:
1x Frame
1x Panel

Operations:
Transport: n* Conveyors
Production:
- Frame: Cutter 1/2
- Panel: Printer 3
- Assembly: Robot 1/2

(optional is Packaging: Packaging Machine 1/2)

Workpiece 2: Papers
Parts:
1x Paper

Operations:
Transport: n* Conveyors
Production: Paper: Printer 1/2/4 (depending on size and quality approach)
(optional is Packaging: Packaging Machine 1/2)

Workpiece 3: Glass/Metal Art
Parts:
1x Glass or Metal- Workpiece

Operations:
Transport: n* Conveyors
Cutting Raw-Materials: Cutting Machine 1/2
Printing: Printer 5
(optional is Packaging: Packaging Machine 1/2)

Figure 11: Products and operational plans (own illustration)

Every workpiece has a **list of possible machines** that match the production requirements by capabilities and is going ahead with requests to make contracts with the machines as introduced by Keddis et al. (2014). This is later introduced in section 3.5.

3.2.3 Mutability challenges in the "printing shop" scenario

Given the production scenario of the previous section, we further apply the idea of a CPM on the printing shop to draw upon some implications of this approach. According to the tasks and routines of a printing shop, different adaptability and mutability challenges for the CPPS are conceivable to be solved by CPMs and CPSs, some examples:

1. Complaints about production outputs of former production lots can influence the current input. E.g. a bad color delivery can decrease the quality of manufacturing outputs. The quality assurance can detect this current deficit and create a change request to avoid the negative effect in future production lots.
2. The current production process can influence the next production input (e.g. a bad color delivery sticks the ink cartridge and a change request of future input is formulated by a machine itself). By the capability based market approach, this can be handled efficiently in updated operational plans and schedules.
3. An individual demand of the current stakeholder such as a special property wish of customers (e.g. different color) can be considered within the current manufacturing input as well as feedback from stakeholders (e.g. former customers who complain about their product and suggest to alter the manufacturing process). This results in adapted market curves due to the elasticity value of the workpiece that is very demanding.
4. Former production outputs can influence the current production (e.g. a logistic bottleneck can lower the current production speed). CPSs later in the process can influence the current CPS (e.g. a predicted maintenance time frame of a machine can change the selection set of a CPSs optimal successor). Again, this can be achieved by capability based planning affecting the CPM.
5. Spontaneous demands such as a special color for the current customer, as well as feedback from former customers can be considered in current production lots.

In order to realize the production process, a complex interplay of the production system components is necessary. For example, a workpiece intends to be processed by a machine. Here, it has to choose between several available color machines, has to find arrangements with several conveyors or other logistic equipment, has to find an agreement with other workpieces to be processed as well and so forth. Each CPS is interacting autonomously based on its autonomy and elasticity brought in the market to realize a cooperative planning solution. Later, different decision strategies might be considered as well.

3.3 Trade-off of local and global objectives

The overall idea of the printing shop is supported by a business logic that ensures economic efficiency (profitability) of the system. Resulting global objectives of production systems can be:

- Reduction of waste,
- Reduction of wear and tear,
- Cost-effectiveness,
- Timeliness,
- Shortest throughput times,
- ….

In contrast to them, each market participant can have distinctive, local objectives:

- Proper Timeliness,
- Proper cost-effectiveness,
- Proper shortes throughput times,
- ….

Sometimes, local and global objectives can be integrated as e.g. a local cost-effective production on a CPS takes part in reaching a global cost-effectiveness w.r.t. the whole CPPS. Mostly, a local cost-effectiveness has to be neglected since a global cost-effectiveness can be improved because of a production order, which prefers two further CPSs. Here, a trade-off of local and global objectives has to be found w.r.t. several objective dimensions, which is in case of the CPM the Pareto optimum. So far, only the cost-effectiveness is considered, within the CPM as an initialization point. Furthers can be handled similarly and serve for optimization as well.

Normally, a production system needs a set of equipment, which consists in case of the online printing shop manufactory of printing machines, cutting machines and so on. Besides that, it needs a place for production and workers. Therefore, the costs can be divided in two parts, fixed costs and variable costs:

- **Fixed costs** are costs that do not change with an increase or decrease in the amount of goods or services produced or sold. Fixed costs are expenses that have to be paid by a company, independent of any business activity. In terms of output volume, these costs are fixed, so that we speak of fixed costs (Frambach 2013). A typical example is the costs of equipment, and something like salary, rent and depreciation charge.
- **Variable costs** vary with production output. Variable costs are those costs that vary depending on a company's production volume; they rise as production increases and fall as production decreases. The variable costs therefore vary with the output quantity (Frambach 2013). The variable costs usually conclude direct material, direct labor and so on.
- Fixed costs and variable costs comprise **total cost**.

In our project, we want to make the printing shop an "intelligent factory", i.e. reaching a high level of autonomy. Compared with normal printing shops, our printing shop tries to use optimal degree of machine labor or human interventions by means of the introduced CPM. In this printing shop, the control system can analyze the orders, then make the decision of producing sequence, time and technological process, hence a big part of costs will be reduced, and another great problem, stock control, will be also well solved, which is a fact that has to be considered within a practical validation.

For implementation, the market transactions leading to cost and benefit calculations, we suggest to use a virtual currency (i.e. bitcoin) to calculate the budgets (c.f. outlook section 5.3).
Until now, according to the material, we offer four types of printing service, which are paper, glass, metal and panel. From this portfolio, we can see that in the production we need engraver, printer, robot, cutting machine, conveyor and packaging machines. Figure 12 shows the budget of the printing shop. The initial budget refers to the local market prices.

To ensure an economically profitable production, we suggest giving the workpieces a starting budget to spend for making contracts. This budget is calculated by subtracting the fixed production costs from the customer paid price in the shop (depending on the contract, that is made by product type, size, quality and delivery times). During the production, the workpieces spend the budget for making contracts with the machines and workpieces to be processed. The difference between budget and variable costs, which mean the expenditures during market transactions, leaves a margin on the workpiece (either a positive or negative one). This is after all the profitability of a single contract. By using more enhanced approaches integrating machines and fixed costs calculations, further research can enhance these basic assumptions that are a sufficient starting point for simulating the market so far. It would be conceivable in further development to use a target costing approach for dynamic pricing for this purpose.

During the production, it can be that the work piece is running out of money because of bad negotiations. We identified two options for not sufficient budgets to ensure the full money-backed production: Either the CPPS is asking the customer for additional financial compensation (i.e. "sorry, we could not produce your order for the given price until the intended date"). Here, the customer can put further money to the production such that the product can be produced in time, or the customer is willing to wait until the product can be produces cheaply e.g. because of free production slots. Here becomes visible, that completely new business models and versions of contracts can realize more flexible, cheap and resource optimal productions. Alternatively, the company can decide to handle non-sufficient budgets with an internal compensation by a cyber-physical production system bank (CPPSB) that serves as a lending platform within the production system. This, of course, is subject to further research and will be outlined in the outlook section 5.3.

Customer Price (depending on contract – product type - size, quality and delivery time (speed))

- (Partly) Fixed costs (production hall, buying of machines...)

....

= Budget for workpiece (for paying internal variable costs in the virtual market)

- Variable costs (market transactions)

....

+/- margin on the workpiece

a) Workpiece has enough money to reach delivery time
b) Workpiece has not enough money to reach delivery time (criterias are not reached)
    a. Asking the customer
    b. Asking a bank and do it internally

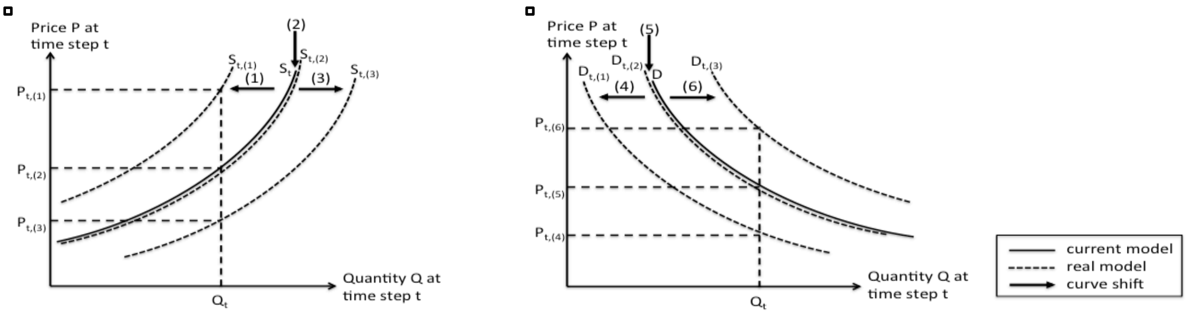
Figure 12: Budget calculation and implications (own illustration)

3.4 Adaption of market mechanisms

The adoption to changing market situation by the CPSs is further described by a shift of the demand and supply curves. This mechanism defines the core of adaptability within the CPM. Six assumptions related to demand and supply in the CPPS were defined in order to suggest an adaptive mechanism to price-amount constellations within the CPM. Each leads to a strategy for the individual CPS. The assumptions describe patterns of reaction by the CPM participations according to the number of requests (on supply side) and the number of offers (on the demand side) they got during the contracting phase (introduced in section 3.5):

- Machine, conveyor, human (M/C/H) - supply side:
  - Assumption 1: If many requests, M/C/H is too elastic in pricing.
    - Strategy 1: curve goes left, hence the price rises.
  - Assumption 2: If one request, M/C/H perfectly fits the market.
    - Strategy 2: no curve change, hence the price is not adjusted.
  - Assumption 3: If no request, M/C/H is too inelastic in pricing.
    - Strategy 3: curve goes right, hence the price shrinks.
- Workpiece (WP) - demand side:
  - Assumption 4: If many offers, WP is too elastic in pricing.
    - Strategy 4: curve goes left, hence the price shrinks.
  - Assumption 5: If one offer, WP perfectly fits the market.
    - Strategy 5: no curve change, hence the price is not adjusted.
  - Assumption 6: If no offers, WP is too in inelastic in pricing.
    - Strategy 6: curve goes right, hence the price rises.

Those six strategies have been visualized in Figure 13. Strategies on demand side have been grouped in (a) and strategies on supplier side have been grouped in (b).



(a) demand curve shift strategies strategies 1,2 and 3

(b) supply curve shifts strategies 4, 5 and 6

Figure 13: Demand and supply curve shift strategies (own illustration)

On this figure, one can see the demand curve D_t or the supply curve S_t w.r.t. the quantity Q at a given time step t and the corresponding price P at that time step. While the straight line represents the current model of the CPS, the non-transparent, real model is visualized with help of dashed lines. Focusing only on the current quantity Q_t at time step t, on each side, there exist one of three possible real prices $P_{t,(n)}$ in relation n to the price of the current model P_t: Either the real price is too low ($P_{t,(1)}$ or $P_{t,(6)}$), the real price is too high ($P_{t,(3)}$ or $P_{t,(4)}$) or it is equal ($P_{t,(2)}$ or $P_{t,(5)}$) to P_t. Corresponding to the relation n, the strategy n is carried out, to correct the price of the next time step P_{t+1}. In an step wise manner, the prices are adjusted iteratively.

The idea to shift curves of the models within each CPS in order to mirror them to real and non-transparent relations in the long run leads to the possibility to interpret prices of the current model as indicator for its degree of capacity utilization. E.g. if a machine was involved in by every time step multiple times, its price would increase and expensive. Inelastic machines could be interpreted as bottlenecks. Here, the integration of similar machines in the CPPS was sense full. The concrete design of those KPIs still is a subject to research (c.f. outlook chapter).

3.5 Contracting: negotiation and scheduling

As already introduced within the literature review, several approaches for market contracting in different settings have already been developed by scholars. Following Fasli (2007), we distinguish auctions and bargaining as two possible approaches for reaching agreements. It has not always been made explicitly clear by scholars how to differentiate between these two categories and which path they followed. As negotiation based on bargaining matches our requirements of real world convergence better than auctions, we decided to go along this path. However, in the outlook we shortly describe perspectives that auctions could bring within the CPM.

Following the definition of (Fasli 2007, p.253), a bargaining situation "is a situation in which two or more agents have a common interest and could reach a mutually beneficial agreement, but have a conflict of interest about which one to reach. To put it simply, the agents would like to cooperate to reach an outcome, but they have conflicting interests". Figure 14 visualizes these conflicting interests building on the Pareto optimal price P^* at a certain time step.

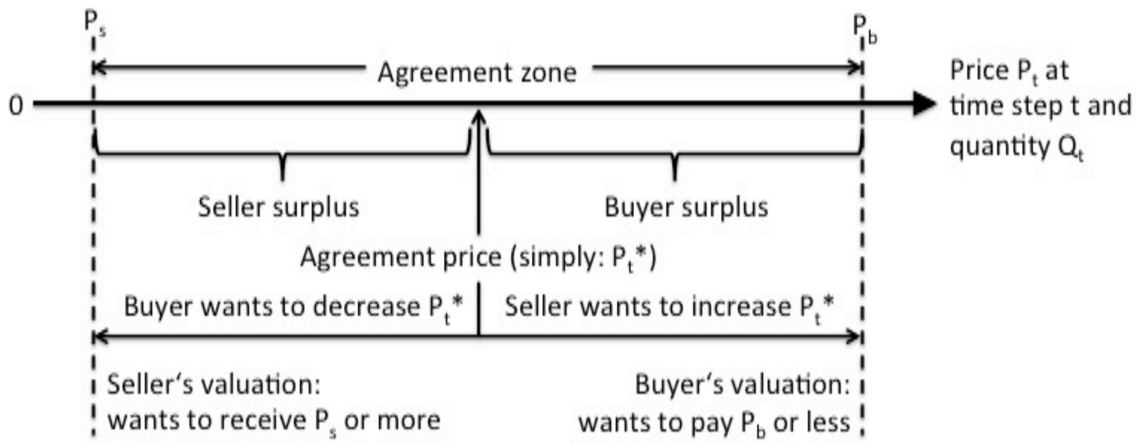


Figure 14: A typical bargaining situation (own illustration following Fasli ,2007, p.253)

Both, the seller and the buyer have a valuation of a certain production performance in form of a price, which limits the so-called agreement zone. The lower border is coming from the seller side and is called P_S and the upper border from the buyer side and is called P_b. Although they would meet in the market at P_t* and each can realize a surplus, the buyer still wants to decrease it and the seller still wants to increase it. This results in an non-solvable conflict.

In order to ensure the efficiency of the bargaining process on the CPM and determine an equal level of bargaining power (c.f. Fasli 2007, p.253), we assume as follows:

- First, to avoid the risk of breakdowns, meaning disagreements due to factors out of control, we assume that in our scenario all CPM players have the same attitude towards risk, they are both equally risk neutral and equally patient to split the gains from trade equally (c.f. Fasli 2007, p. 253).
- We further assume that outside options (e.g. other offers) do not have a direct influence on negotiation as we have set certain time frames to be processed and all offers arrive at the same time to ensure no influences can occur.
- There is also full transparency in the CPM (no asymmetric information). This leads to efficient bargaining outcomes (c.f. Fasli 2007, p.254).

According to a contract made with the customer, every good has to be processed within a certain time frame. Time dependent relations are visualized in Figure 15 and related as follows:
Following the operational plan of a single workpiece and having this workpiece with DoA = 1, a time optimal order of CPS can be identified, that is required to complete workpiece W_A. In this case, it needs 8 time steps. Since the assumption of DoA = 1 has to be relaxed and the CPM can be located at Figure 6 (b). That 8 time steps would seldom occur and a contractual buffer can be identified until the end of the contractual time frame.
Faced with the time optimal operational plan of a workpiece, a contractual buffer can be identified. To ensure this timeliness, every workpiece has to make its deals with the machines conveyors, etc. in time and has time reserves as the contractual buffer shows.
Assuming each CPS to have a *view* over the entire contractual time frame, and all order combinations are processed, compared, contracted, etc., the processing becomes quite extensive and inflexible. Further, each CPS has a willingness to consider every offer combinations of a certain time step, which is called *depth*. This is inspired by the idea, that even professional customers do not screen the entire market. They reduce themselves to a number of offers and choose the best alternative.
In our proposed solution, we use those heuristics whose mechanisms follow the realistic imaging of real market negotiation in order to reduce the complexity.

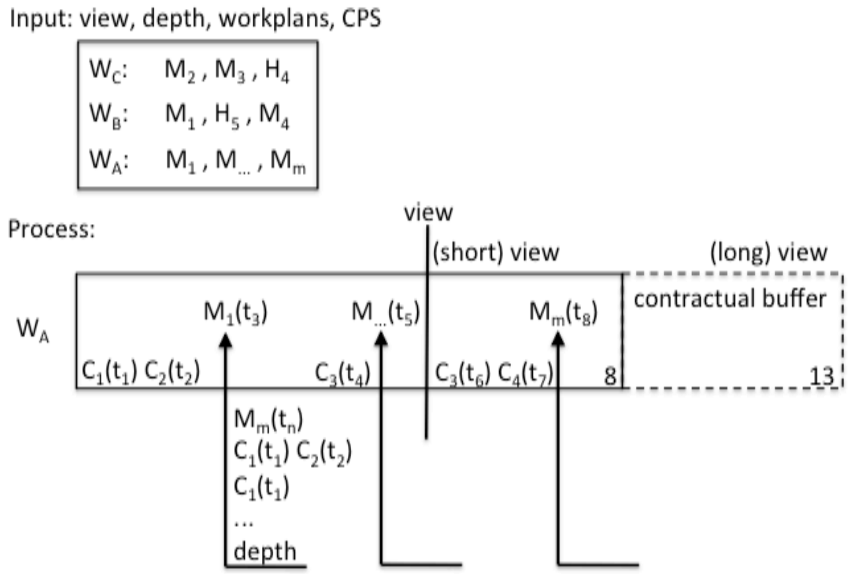


Figure 15: Heuristics for contracting (own illustration)

The process of negotiation is initiated by the customer that calls for offers transmitting requirements in the market sessions. Basically, first, the *negotiation_status* is set and given by a tact (event-oriented). Thus, the suppliers evaluate the call-for-offers, decide which subtasks to make an offer upon, and return offers through the negotiation session. Next, the customer received the offers from suppliers. If there is a match of interests between the market participants, the customer awards contracts to the selected suppliers. Otherwise, further bargaining is done. The six market adoption strategies refer to the six assumptions in section 3.4.

If we look at this process on a code base, firstly an overview is given and then the code (c.f. Figure 16) is explained line wise. In order to realize the process of negotiation, we use three for-loops to process. The first *for-loop* goes through all machines in the operational plan and asks for the availability for a certain time-step needed. The second *for-loop* repeats this procedure for all conveyors that link the machines to ensure transportation of workpieces. This is done on a certain sight (*view*) that serves as an input variable to set the length of contracting into the future. A shorter view ensures greater flexibility in contracting, e.g. to changing market conditions, whereas a longer view is ensuring both time and also quality availability. The third *for-loop* then processes all requests and offers as follows:

- The agent workpieces check for all possible required machines in the next production steps in time *t*, according to the variable view. Going through the *first and second for loop* (l.6-8) of needed machines it sends requests to every machine about the requirements *(time, properties[])*, where *properties[]* serves as an array for the defined requirements (l.9). After that, the workpiece waits for concrete offers by the required machines till the bid deadline ends (l.10). Same procedure is done for the needed conveyors as a means of transportation (l.30-32).
- At the requested machines and conveyors, we assume them to know a starting reservation price according to the production expenditures and variable costs that is asked to be the minimum willingness–to-sell price (l.61-63). For our scenario we assume a reference point (1;1) as a starting point for the market price, which is Q_t and P_t as they can be found in Figure 13. Agents collect all requests and filter them by feasibility of requests as they compare the required actions with their own capability and scheduling list (l.63-65). The processed filtered request list is now processed by a *for-loop* making an offer to workpieces at the market price per every *req(t) (l.66-68)*.
- At the demand side, the workpiece goes through a third *for-loop* processing all acquired offers to compare with its reservation price which equals its maximum willingness-to-buy price (l.11 and l.33). If the respective offer price is under the *reservation_price* and the budget of the workpiece ensures the *availability_to_pay* the workpiece is forced to accept the lowest of all suitable offers for the certain time frame, sending an *acknowledgement* to the machine and paying the price to fulfill contracting immediately. This leads to a machine or conveyor booking at *m(t,id)* respectively *c(t,id) (l.17 and l.39)*. After this, the adoption mechanism of the pricing curves is fulfilled as described in section 3.3.4, leading to different adoption strategies described before (l.18-29 and l.40-52). Thus, the adoption due to elasticities is a major idea of the market approach.
- The same adoption procedure applies to the supply side (l.69-80).
- In case, no contracting was possible the procedure is stopped (l.56) or re-contracted (l.94). Here, the variable negotiation_status can be updated and progress a system wide tact rate.
- Finally, after contracting the agents (workpieces) are moved to the next place (l.84-92).

All in all, we use the general idea of one-way-offerings by the suppliers (machines, conveyors) in our negotiation approach and link the overall process with the introduced adoption to changing market requirements by a shift of demand and supply curves. Heuristics serve to reduce the complexity.

As all agents have impatience as cost of time changes their elasticities, there is a friction in bargaining to prevent deadlocks.

```
negotiation_status = 1 # given by tact (event oriented, set when a work is finished
while (negotiation_status == 1){ # Do negotiation

If (agent=workpiece){
    # Check for all possible required machine(s) in next production steps (variable=view) in operation plan
    for (ma=1, ma<= MA*view, ma++){
        # Contracting
        for (t=tmin, t<= tmax-tMa_min, t1++){
            tell machine about demand requirements (time, properties[]),
            wait for offers till bid deadline
                for (offer=1, offer<=offerMax, offer++){
                    compare with reservation price (maximum willingness-to-buy)
                    if (offer_i < reservation_price && budget (availability_to_pay) > reservation price){
                        accept lowest offer
                        send acknowledgement to machine
                        pay lowest offer price # contracting
                        book m(t,id)
                        # Adoption of the price curve after contracting
                        if (offer_count>1 && offer_count_smaller_than_reservation_price>1){
                            strategy 4
                        }
                        else {strategy 5}
                    }
                    else{
                        strategy 6
                        # alternative: make a counter offer with reservation price
                        # wait for answer
                    }
                }
                for (conv=1, conv<= Conv*View, conv++){
                    tell_conveyor_about_demand_requirements (time, properties[])
                    wait for offers till bid deadline
                    for (offer=1, offer<=offerMax, offer++){
                        compare with reservation price (maximum willingness-to-buy)
                        if (offer_i < reservation price && budget / availability to pay > reservation price){
                            accept lowest offer
                            send acknowledgement to machine
                            pay lowest offer price
                            book conv(t,id)
                            # Adoption of the price curve
                            if (offer_count>1 && offer_count_smaller_than_reservation_price>1){
                                strategy 4
                            }
                            else {strategy 5}
                        }
                        else{
                            strategy 6
                            # alternative: make a counter offer with reservation price
                            # wait for answer
                        }
                    }
                }

        }
        if (ma -> no offer acceptance){
            break # later proof of machines does not make sense any longer
        }
    }
}

If (agent=machine/conveyor) {
    reservation_price = get reservation price (minimum willingness-to-sell)
    set market price == reservation_price
    collect requests (time, properties[])
    req_fe = filter requirements by feasibility (all requirements) # with capabilities
    for (req=1, req<=req_fe; req++){ # loop for offerings
        make an offer to workpiece at market price per req(t) # *P (Data Analytics approach possible - see outlook)
    }
    # Adoption of the price curve after contracting
    if (contract(t){
        if (no_req_fe(t)>1){ # all feasible requests at time t
            strategy 1
        }
        else {strategy 2}
    }
    else{
        strategy 3
    }
}
}

# Movement of agents

If (negotiation status == 0 && agent.next == null) {
stay
}
else if (negotiation status == 0) {
go to agent.next
}
else if (negotiation status == 1) {
wait for requests
}

# Optional: Re-negotiation phase

```

Figure 16: Code inlets for the negotiation algorithm (own illustration)

4. Conception of an agent-based simulation model

4.1 Software paradigm choice

In order to test and validate the CPM including the negotiation mechanism (see chapter 3.5) within the production scenario (see chapter 3.2) and on top of that consider the adaptability and mutability challenges (see chapter 3.2.3), a simulation approach is indicated. As introduced in the literature review (see chapter 2.5), an agent-based approach could be promising (e.g. Matsuda et al. 2012). To ensure this first idea, we did a comparison of individual approaches within the group.

Basically, simulation is an approach for analysis of systems that are too complex for the theoretical or formulaic processing. This is the case mainly in dynamic system behavior such as within production systems. In the simulation experiments are carried out based on a suitable model to gain insight into the real system. The sequence of the simulator with concrete values (parameterization) is called a simulation experiment. Its results can be interpreted and transmitted to the real world system. In order to simulate the system several approaches have been conducted and compared as Table 3 summarizes:

	Structural Program-ming	**Object - oriented Program-ming**	**Agent-based Program-ming**	**Discrete Event Simulation (DES)**	**System Dynamics (SD)**
Representative	C in Eclipse	Python in Eclipse	AnyLogic, Python	SimPy	Vensim
Implementation	Expensive	(Rather) Cheap	Cheap	Cheap	Cheap
Main idea	I.e. control flows, loops for system design (structural perspective)	Objects as system representatives (object / polymorphy perspective)	Agents as system representatives (micro perspective)	Discrete Events as control for process flows to take actions (process / event perspective)	Equations as system representatives (macro perspective)
Simulation	Compiling and Testing	Compiling and Testing	Simulation environment included	Simulation environment included	Simulation environment included
Practicability	Machine near programming language	Translation to machine readable code needed	Translation to machine readable code needed	Translation to machine readable code needed	Translation to machine readable code needed
			Combined multi-method-approach supported by AnyLogic		

Table 3: Software paradigms in comparison (own work)

For simulation outside the production environment, we have chosen *Agent-based programming* as the most suitable approach - a programming paradigm where the construction of the software is centered on the concept of software agents. In contrast to object-oriented programming, which has objects (providing methods with variable parameters) at its core, agent-based programming has externally specified agents (with interfaces and messaging capabilities) at its core (for detailed comparison see Table 4). They can be thought of as abstractions of objects. Exchanged messages are interpreted by receiving agents. This fits explicitly well to our proposed negotiation mechanism.

	Object oriented programming	**Agent-based programming**
Basic unit	object	agent
Parameters defining state of basic unit	unconstrained	beliefs, commitments, capabilities, choices
Process of computation	message passing and response methods	message passing and response methods
Types of message	unconstrained	inform, request, offer, promise, decline

Table 4: Object oriented programming vs. agent-based programming (Shoham 1993)

Agent-based programming comprises several techniques and methods to simulate real world problems on a micro-system level. The most important concept is the state chart, a visual construct that enables programmers to define event- and time-driven behavior of various objects. State charts consist of states and transitions. A state can be considered as a "concentrated history" of the object and also as a set of reactions to external events that determine the object's future. The reactions in a particular state are defined by transitions exiting that state. Each transition has a trigger, such as a message arrival, a condition, or a timeout. When a transition is taken, the state may change and a new set of reactions may become active.
Following Borshchev (2013), Figure 17 visualizes the relations of states and transitions on the leften side based on a simple example and on the righten side, the event-based interplay of two agents, which changes on base of the history (current states) of the agents.

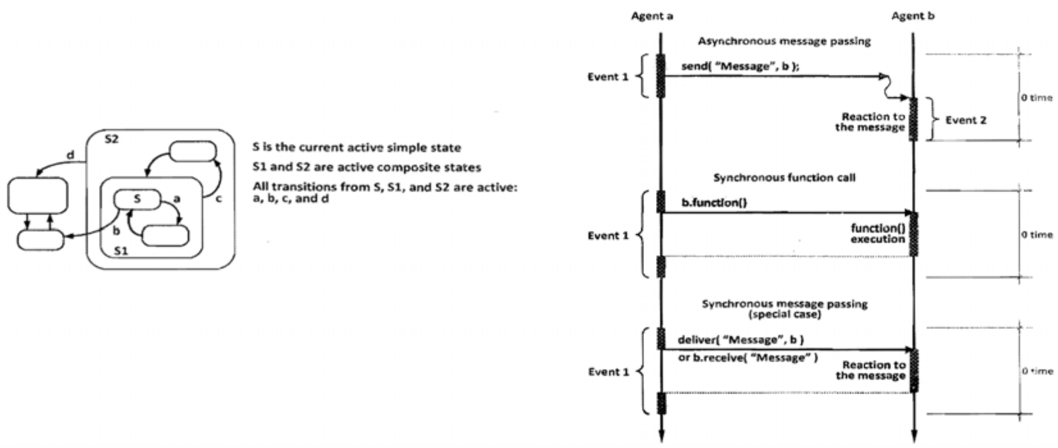


Figure 17: Agent-based approach (Borshchev 2013)

In our opinion, this state-chart message oriented concept implemented in Agent-based software is very likely to be used to get the cyber-physical market concept to a further simulation stage, since the bargaining (negotiation) process could be implemented based on this paradigm. However, for simulation in a real-world production environment (i.e. AZI), it will be necessary to transfer these approaches to machine-near languages (i.e. *C*) or suitable frameworks such as *Python Arduino for Raspberry Pi*.

4.2 Further steps for simulation

There is different simulation software available to choose from, e.g. *Simul8 or Adonis*, both useful for Business process management and simulation. *AnyLogic* was chosen for the experiences that group members brought with. On the *Chair of Business Informatics, esp. Processes and Systems* prefer it is preferred because of its extensive functionality.
In the following, a step-by-step list for simulating our CPM backed production scenario is given. The simulation was not finished due to a lack of expertise and time. The checkmarks indicate which steps could be fulfilled.

• Factory layout [breaking down to the minimum setup]	✓
• Agent population (machine, workpiece, conveyor, queue) [e.g. what configurations can be made, what goes into "outlook" and for the next groups, what's possible within our AnyLogic project until today]	✓
• Movements of workpieces	
• Initialization of workpieces with budgets and operational plan, machine capabilities	
• Negotiation and scheduling based on state charts and by using *Optquest* solver	
• Integration of market demand and supply curves	
• Pareto optimal solution	

Table 5: Ongoing to-do-list for simulation of proposed concept (own work)

Such a simulation shall ensure, all eventualities and parameters, that can influence the order and the steps the algorithm takes, are tested out. The proceedings have to be reviewed to evaluate the worth of e.g. additional functionality like using underlying functions to handle delays within the production and to solve other issues within the programming.

4.3 AnyLogic as simulation framework

Using *AnyLogic* to verify our findings was the right choice since there exists a sufficient amount of documentation by the company and also by external authors on how to create similar prototypes. Also *AnyLogic* has a set of objects implemented that are easily configurable to match our needs.

Below you can find an illustration of a basic state chart implementation as well as elements of the process modeling library, shown in the lower half of Figure 18.

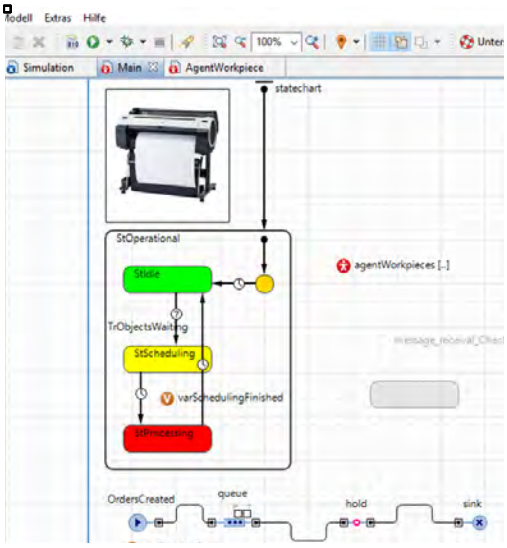


Figure 18: AnyLogic system design (own illustration)

To simulate the creation and deletion of agents of the type workpiece including parameters and functions, the process modeling library offers preconfigured elements such as queues, where the workpiece agents can be waiting for the next production step. The second library we used is the one for state chart elements, as can be seen in Figure 19.

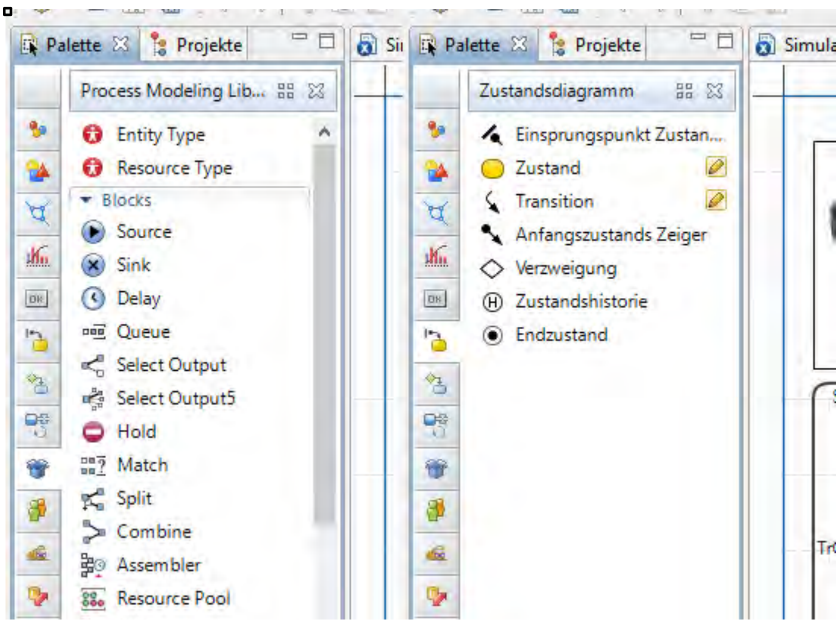


Figure 19: AnyLogic system elements (own illustration)

In order to stick with the simplest possible demonstration, we used only one machine that is idling at the beginning of the demonstration. As soon as the process modeling object of the type "source" introduces the first agent of the type workpiece, the machine switches to the state of scheduling between all waiting objects. When this is finished, the state of processing said workpieces is reached. Independently, the "source"-element introduces new workpieces, and puts them in queue line, which can be seen on the bottom of Figure 20. Here, each rectangle is standing for a workpiece, which is currently produced.

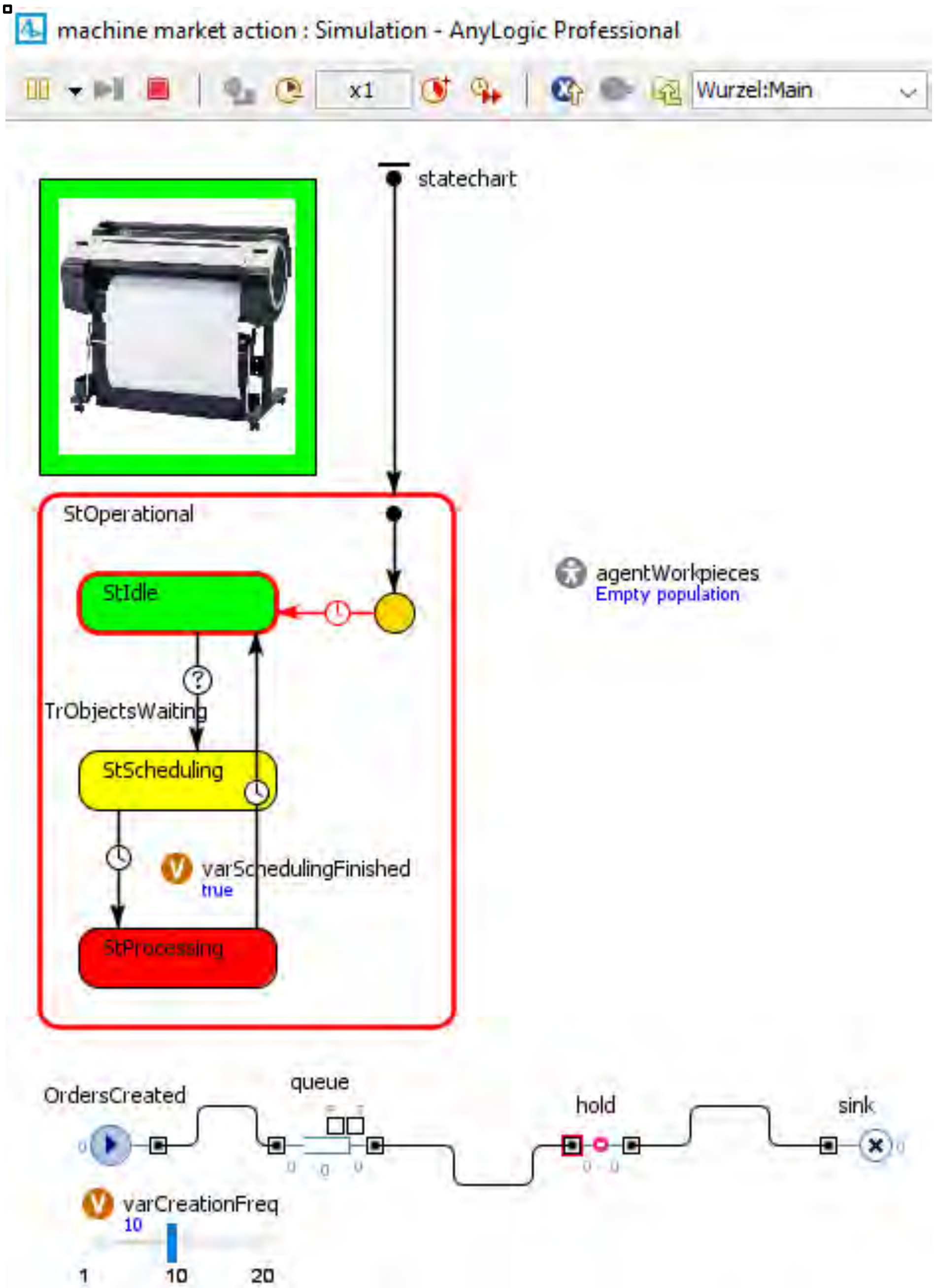


Figure 20: AnyLogic state charts (own illustration)

So far, the simulation uses an object of the process modeling library called “hold”. To further simulate with *AnyLogic*, the object “hold” may be replaced by an “assembler”. Also to further extend the simulation to all actual processing steps, such as workpieces in queue and the movement between machines, an object of the type “conveyor” is being introduced - both part of *AnyLogic’s* basic objects. Figure 21 visualizes those graphical examples.

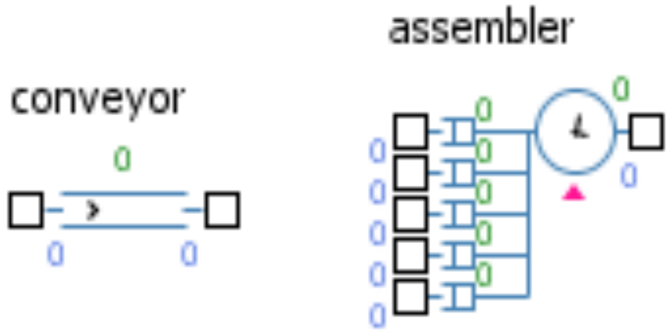


Figure 21: AnyLogic objects (own illustration)

Moreover, *AnyLogic* helps to easily understand the states and internal variables that objects are in at runtime. Here, simply clicking on an object lets the corresponding dialogue window appear. This realizes a click and test experience, which simplifies the further realization a lot, and can be seen in Figure 22.

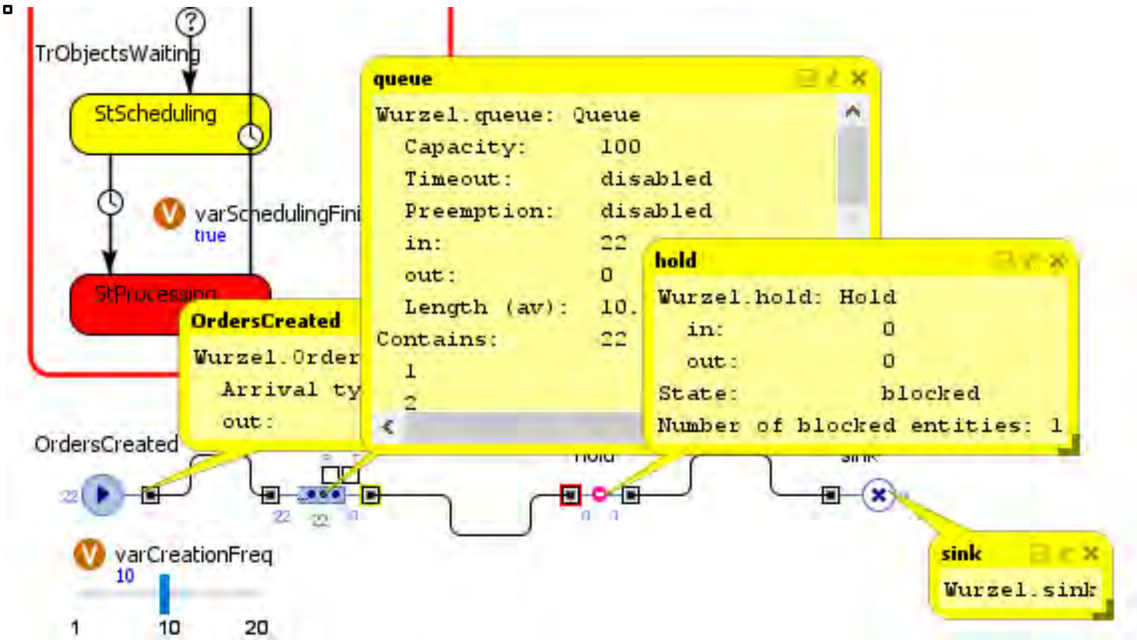


Figure 22: AnyLogic states and internal variables (own illustration)

5. Concluding Remarks

5.1 Summary

Our main contribution lies in the opening of a new research field for autonomous system design using CPMs. We presented a new approach for autonomous production systems utilizing market transactions based on demand and supply market mechanisms. According to the degree of autonomy (DOA) introduced by Gronau et al. (2015), the market participants within cyber-physical systems interact autonomously according to changing and adapting elasticities. Inspired by the idea of mutability the economy of markets within CPSs could enhance self-adaptability in production systems. An introduced mechanism for demand and supply curve shift within the proposed negotiation between CPSs is presented for a perfect market. The perfect market is designated with rational behavior and utility maximization.

When the system is properly set, it seems obvious to use a traditional manufacturing steering with a hierarchic approach. A poorly coordinated factory might regulate itself by human intervention and hierarchic ERP/MIS steering. However, again the idea of mutability of systems seems beneficial as the response capability of the system increases in a more decentralized scenario. Even a perfectly coordinated factory could benefit from the proposed market-based approach to face changes earlier, i.e. to react to altered purchasing behavior by customers in a very flexible manner. Besides, the advantages of the presented approach are the more obvious the greater the turbulences interact within and onto the system. Our introduced bargaining process based on elasticities of machines and workpieces leading to a shift of market demand and supply curves is able to react to changing economic situations. The degree of autonomy could be a suitable moderator to calibrate the system suggesting a DOA smaller than 0.5 most probably as a best fit (Gronau et al., 2015). Again, further simulation approach is beneficial to validate the theoretical assumptions. Based on the results presented in this paper, a validation and verification is in scope for further research.

5.2 Critical appraisal

5.2.1 Research questions

The main research dealt with the following question: What issues can we address when putting real market principles on a production environment, and how? Therefore, we extended the research approach by Gronau et al. (2015) with a CPM conceptualization, that uses demand and supply curves for autonomous self-regulation in CPSs. We further looked at suitable mechanisms to coordinate market participation. Thus, a real-life inspired negotiation algorithm is introduced. Further, we discussed several issues concerning the question about what problems may be solved in a self-organizing production scenario by CPMs. Finally, we cope with several questions in an extended outlook: What new paradigms can be used for scheduling, internal pricing or adaption to change by environmental disturbances?

5.2.2 Methodology

Due to artifact building design science approach within the aforementioned research questions we followed DSRM by Peffers et al. (2007) which worked well for the introduced research. Since a demonstration is still left, it has to be critical appraised, if a simulation is adequate for the hypothesis validation (c.f. section 2.1).

For the validation purpose, design science research should present a compelling scientific theoretical foundation with an emphasis on the central features of scientific research - abstraction, originality and reasoning. The validation of research presents a particular challenge. A full validation through a formal proof or by an empirically confirmed substantial theory is not an option for our real world artifacts. Therefore, the only possibility is to make all assumptions underlying the draft design explicit (Frank, 2000). Four steps to ensure rigor in validation are proposed by (Rand and Rust 2011):

- First, a micro-face validation proves if the elements of the implemented model correspond "on face" to the real world.
- Second, macro-face validation proves if processes and patterns implemented do so as well.
- Third, an empirical input validation checks if the data used corresponds to the real world.
- Finally, empirical output validation ensures that the output corresponds to the real world. Cross-validation can be used to compare a further model to a previous model already been validated.

Pareto optimality is indeed a situation where it is not possible to improve the situation for a CPS without simultaneously worsen another one's situation. The proof is in our case within a closed system, where it is possible to know all market participants and to compare any existing states.

5.2.3 Overall results

The proposed approach using market transactions within production systems is very promising. We mainly focused on steps 1 and 2 of the presented LSWI research paradigm - meaning to bring a concept of CPM into life.

5.2.4 Single results

Finally, we want to summarize our current single results. As the focus of the project is grounded within the LSWI project research cycle, we accomplished the following results:

- critical reflection of the current state of the art in research by a literature review,
- creation of a realistic production scenario for practical application,
- brief introduction of the CPM-based approach for flexible CPPS,
- adaptability and mutability challenges of use cases concerning strategy within the proposed scenario,
- development of a real-world inspired negotiation algorithm for interaction of CPSs,
- proposal for practical implementation and
- derivation of relevant further research questions during the project.

5.3 Outlook

During the project work on the CPM concept, we identified several promising extensions to the core idea as well as research gaps to the virtual market based approach in CPPSs. Thus, we want to briefly outline a few further issues for scholars.

Game theoretic strategies (e.g. Wooldridge 2009)
Game-theory in general is the study of modelling decisions of rational decision-makers, and taking the findings into account when taking action for oneself (Bicchieri 2006). A game-theoretic approach can be used either to extend our real world factory scenario of a printing shop and on our limited projection our algorithm is based on. In Game theory, two agents influence each other, and by cooperation with or hindrance of the other agent result in different overall utilities for both agents. In a case of low number of suppliers, but steady or increasing demand, the CPPS could try increasing prices without fearing the loss of orders. While gaining short-term utility, in the long run there may be a decrease of utility occurring, as other suppliers change strategies too, or long term contracts run out, due to the influence of human psychology here. This approach could be implemented by utility functions such as for example $u = w_x*x+w_y*y+w_z*z$ with different strategies $[w_x, w_y, w_z]$ by the market players.

Another example is based on the use of aggressive strategies on workpiece agents. Companies A and B are competitors and use a CPPS to have their good processed. The workpiece agent of client A could increase A's overall utility over client B by overbidding B in crucial steps of the manufacturing process, or increasing the price, B has to pay, to finish the processing of goods, harming B financially. Over the long-run, B and the owner of the CPPS could adapt to these strategies, resulting in a damaged business relationship between all three participants.

When implementing game-theoretic dealings the idea is to give the machines in our scenario reasons and the ability to aim for actual profits when being in use. If well managed, the whole scenario is capable adjust the final price for producing a workpiece, thus to make profit from the customer without the need of any monitoring by the factory owner. At the moment, machines take the lowest price they need to start working, and raise it, in case the demand is higher than what they can supply. When applying game theory here, every machine and workpiece is ought to think in the most self-centered way possible, and thus uses machine learning to adjust prices in opposition to other virtual market participants. For the start, we assumed, the price a machine agent is asking for, is only the lowest possible, and increases only, if the demand increases.

Game theory approaches could also apply to the objectives and actions of directly competing companies (CPPSs). This may be concerning pricing, but also up- and downsizing or upgrading our production environment or lowering our production volume. To give a good example on when a game-theoretic approach would be lead to inefficiency in the market, the following, very limited scenario may be proposed: There is one machine agent that does cutting. Workpieces have to get cut, but cannot decide between machines. In that showcase, an egoistic cutting machine could ask for the highest price possible, and lowers it, until there are any workpieces accepting the offer; a monopoly is created. This example could influence other approaches such as a limited budget per workpiece.

Negotiation e.g. with auctions (e.g. dutch auctions)
During our project, different ways of negotiating prices have been discussed, e.g. the use of a Dutch auction, where the auctioneer starts offering a very high price, lowering it until a bidder is found to pay it. This is actually a way to influence the make use of the available financial resources, that would not be used up, in case the machinery starts with the lowest price possible. Workpieces and machines may be using different strategies to succeed. E.g. with or without self-learning algorithms implemented, they could react very different, when e.g. taking earlier auctions, where they did not succeed, into account.

Integration of a central financial institution (Bank)
If the level of autonomy and perhaps level of human behavior of system components rises or the CPPS has to interact with external parties, financial transactions have to be confirmed by an independent authority, which we call cyber-physical production system bank (CPPSB). There is a small number of extensions to the minimal functionality in the proposed model which need a central financial institution, or a supervising authority concerning transactions ensuring trust for market transactions. In the real world a bank or a stock exchange offer such services. As introduced in section 3.3 in one example approach, all workpieces may be controlled directly by the client order, and have a given maximal budget, and a given maximal finishing time:

- Case A (no interference of the factory owner): The workpiece reaches the budget, and can't be processed any further. The client has to manually increase the budget through a factory internal banking transaction. The customer's incentive here lays e.g. on an initially cheaper product, an environmental friendly production only based on free slots, etc.
- Case B (factory guarantee, interference by the factory owner): The factory has an SLA with the client, thus it guarantees e.g. a deadline or a maximal budget that a client has to put onto a workpiece. Hence if the budget is reached, the factory owner may spend internal currency, to get the workpiece processed further.

Use of a transactional Blockchain as public ledger
To fulfil the task of overseeing financial transactions of the workpieces more independently, also a Blockchain technology may be implemented, that asks all participants to confirm all transactions, whether directly involved or not. All participants keep a copy of the history of all transactions. This approach helps, in case the participants cannot be fully trusted (c.f. game-theoretic scenarios). When integrating a virtual currency (e.g. Bitcoin), issues in section 3.3 are addressed. The perfect market definition states, that market participants shall perform immediate responses. With some conventional ways to exchange country-dependent currency at banks, the CPPS and the client cannot work out the pricing reliably and in real-time. A virtual currency, that is used across markets, allows more stable and CPPSs-wide pricing.

Influence of disturbances
Environmental and external influences may impact the machine's decision making process. These influences could be taken account by the individual CPS interacting with the environment and lead to different decisions within the virtual market being linked to. Influences could be for example:

- air pressure
- humidity
- temperature
- strength of light
- noise
- level of sickness of the human workers
- age of replacement parts
- switching between suppliers

Machine Learning / Data Analytics

Machine Learning is part of computer science and takes recognized patterns of historical data into account (Alpaydin 2010). In a CPPS, historic information could be the reliability rate of deliveries by a certain postal service, the failure rate of raw materials such as computer chips, a self-learning algorithm that predicts the need of the replacement of machines by having a link to the customer success management's support ticket system, by linking historic production information to claims made by the customers today. All these approaches seem to be very promising to be implemented.

As another feasible extension to the introduced market model, CPPS could use statistical approaches to reach higher profits by acting similar to nowadays airlines. Airlines like Lufthansa are reserving seats for more passengers than are fitting into an airplane, decreasing the cost of each ticket, since a certain percentage of passengers tend to not show up at the airport, or actively reschedule their flight. This idea is based on binomial distributions and stochastic probability of defaults. Having similar business options in use, the CPPS could also start adapting to default rates of other firms of the supply chain, or similar situations. "Overbooking" may be covered my machine learning approaches, that develop strategies, based on past time information. Integrating further measures, like the cost of rescheduling and delaying an order is part of an implementation of such an overbooking strategy.

Human Psychology

Another interesting issue is the integration of human psychology, either for machine-to-machine negotiation or for human-to-machine interaction. To show the importance of these concepts, we shortly want to introduce a scenario by Felser (2015) that could have a major impact on negotiations in the virtual market. The seller insists the customer to give the first offer. Hesitantly, the customer made an offer of 150 euros - and the seller spontaneously agrees. Most people would now probably think, "I could have had cheaper.", since the seller was indeed immediately agreeable. Maybe as we even exceeded his expectations, an occasion to negotiate was not seen. For human satisfaction with purchase, these considerations are of course poisonous. In fact, people are rather less satisfied when their first offer is immediately accepted then if "tough negotiations" have been preceded. This applies even if the result is worse after a negotiation, as the acceptance of the first offer would have been (Galinsky et al. 2002). The objective result is better, but it is rated worse subjectively. The key appears to be that the price could easily have been even lower in case of immediate offer-acceptance (Galinsky et al. 2002). Galinsky et al. (2002) also show that subjects whose initial offer was immediately accepted, in consequence tended less again to deliver the first offer in a comparable situation. This is another human behavior as the volunteers refrain from an important bargaining advantage, namely the anchor effect, which always favors those who had the first bid in a negotiation (Galinsky und Mussweiler 2001). Since we suggest to implement humans in the interactions of the virtual market, it could be at least necessary to teach machines both a general understanding and reaction patterns on this irrational behavior.

Design of new form of KPIs and business models

As the CPM has the potential to coordinate CPPS in a new manner, new forms of business models can be developed. Starting from a closed production setting, the setting can be opened and integrate further stakeholder and ways of external and internal cooperation. Here, as systematic overview and business model derivation is promising.

Analog to the elasticities as KPIs, further and on building KPIs can be developed and create a new form of controlling instrument. This should be based on practical calculations, as was described in chapter 3.2.2 and should consider at least fixed and variable costs. Here, as systematic overview and KPI derivation is promising as well.

To sum up, we opened a new field of research for autonomous production steering with CPMs. We finally outlined that further experimentation on degree of autonomy and validation by simulation are the next steps to proceed. It is important to examine how stable the system behavior is especially faced with adaptability and mutability challenges, if the solution space is indeed Pareto optimal and stays optimal, how much savings the approach in fact brings (practical validation) and how the integration of further elements succeeds.

Bibliography

Alpaydin, Ethem (2010): Introduction to machine learning. 2nd ed. Cambridge, Mass: MIT Press (Adaptive computation and machine learning). Online at http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=307676.

Al-Sakran, Hasan (2014): B2C E-Commerce Fact-Based Negotiation Using Big Data Analytics and Agent-Based Technologies. In: *ijacsa* 5 (12). DOI: 10.14569/IJACSA.2014.051204.

Bicchieri, Cristina (2006): The grammar of society. The nature and dynamics of social norms. 1. publ. New York NY: Cambridge Univ. Press.

Borshchev, Andrei (2013): The big book of simulation modeling. Multimethod modeling with AnyLogic 6. S.l.: AnyLogic North America.

Brookes, Ian (Hg.) (2014): Collins English dictionary. 12. ed. Glasgow: Collins.

Cezanne, Wolfgang (2005): Allgemeine Volkswirtschaftslehre. 6., überarb. Aufl. München, Wien: Oldenbourg (Wolls Lehr- und Handbücher der Wirtschafts- und Sozialwissenschaften).

Collins, John; Youngdahl, Ben; Jamison, Scott; Mobasher, Bamshad; Gini, Maria (1998): A market architecture for multi-agent contracting, S. 285–292. DOI: 10.1145/280765.280845.

Esmahi, L.; Bernard, J.-C.; Dini, P. (2000): MIAMAP: a virtual market-place for intelligent agents. In: HICSS33: Hawaii International Conference on System Sciences. Maui, HI, USA, 4-7 Jan. 2000, S. 12.

Fasli, Maria (2007): Agent technology for e-commerce. Chichester u.a.: Wiley.

Felser, Georg (2015): Werbe- und Konsumentenpsychologie. 4. erw. und vollst. überarb. Aufl. 2015. Berlin: Springer. Online at http://dx.doi.org/10.1007/978-3-642-37645-0.

Frambach, Hans A. (2013): Basiswissen Mikroökonomie. 3., überarb. und erw. Aufl. Konstanz: UVK-Verl.-Ges (UTB, 8526).

Frank, Ulrich (2000): Evaluation von Artefakten in der Wirtschaftsinformatik. In: Lutz J. Heinrich (Hg.): Evaluation und Evaluationsforschung in der Wirtschaftsinformatik. Handbuch für Praxis, Lehre und Forschung. München: Oldenbourg, S. 35–48. Online at https://www.wi-inf.uni-duisburg-essen.de/FGFrank/documents/Zeitschriftenartikel/EvaluationWI.pdf, zuletzt geprüft am 22.08.2016.

Galinsky, A. D.; Seiden, V. L.; Kim, P. H.; Medvec, V. H. (2002): The Dissatisfaction of Having Your First Offer Accepted. The Role of Counterfactual Thinking in Negotiations. In: *Personality and Social Psychology Bulletin* 28 (2), S. 271–283. DOI: 10.1177/0146167202282012.

Galinsky, Adam D.; Mussweiler, Thomas (2001): First offers as anchors. The role of perspective-taking and negotiator focus. In: *Journal of Personality and Social Psychology* 81 (4), S. 657–669. DOI: 10.1037/0022-3514.81.4.657.

Gericke, A.; Winter, R. (2009): Entwicklung eines Bezugsrahmens für Konstruktionsforschung und Artefaktkonstruktionin der gestaltungsorientierten Wirtschaftsinformatik. In: Jörg Becker, Helmut Krcmar und Björn Niehaves (Hg.): Wissenschaftstheorie und gestaltungsorientierte Wirtschaftsinformatik. Heidelberg: Physica-Verl., S. 195–210.

Gronau, Norbert (2006): Wandlungsfähige Informationssystemarchitekturen - Nachhaltigkeit bei organisatorischem Wandel. Berlin: GITO Verlag.

Gronau, Norbert; Grum, Marcus; Bender, Benedict (2015): Determining the optimal level of autonomy in cyber-physical production systems. University of Potsdam.

Ha, Sung Ho (2010): Agent-Based Decision Making in the Electronic Marketplace: Interactive Negotiation. In: Piotr Jędrzejowicz, Ngoc Thanh Nguyen, Robert J. Howlet und Lakhmi C. Jain (Hg.): Agent and Multi-Agent Systems: Technologies and Applications: 4th KES International Symposium, KES-AMSTA 2010, Gdynia, Poland, June 23-25, 2010, Proceedings. Part II. Berlin, Heidelberg: Springer Berlin Heidelberg, S. 1–10. Online at http://dx.doi.org/10.1007/978-3-642-13541-5_1.

Keddis, N.; Kainz, G.; Buckl, C.; Knoll, A. (2013): Towards adaptable manufacturing systems. In: 2013 IEEE International Conference on Industrial Technology (ICIT 2013). Cape Town, S. 1410–1415.

Keddis, Nadine; Kainz, Gerd; Zoitl, Alois (2014): Capability-based planning and scheduling for adaptable manufacturing systems. In: 2014 IEEE Emerging Technology and Factory Automation (ETFA). Barcelona, Spain, S. 1–8.

Klöpper, Benjamin; Pater, Jan Patrick; Honiden, Shinichi; Dangelmaier, Wilhelm (2012): A multi-objective evolutionary approach to scheduling for evolving manufacturing systems. In: *Evolving Systems* 3 (1), S. 31–44. DOI: 10.1007/s12530-011-9040-3.

Klöpper, Benjamin; Pater, Jan-Patrick; Dangelmaier, Wilhelm (2014): An Evolutionary Approach on Multi-objective Scheduling for Evolving Manufacturing Systems. In: 2014 47th Hawaii International Conference on System Sciences (HICSS). Waikoloa, HI, S. 826–835, zuletzt geprüft am 07.08.2016.

Lau, Raymond Y.K. (2007): Towards a web services and intelligent agents-based negotiation system for B2B eCommerce. In: *Electronic Commerce Research and Applications* 6 (3), S. 260–273. DOI: 10.1016/j.elerap.2006.06.007.

March, Salvatore T.; Storey, Veda C. (2008): Design science in the information systems discipline: an introduction to the special issue on design science research. In: *MISQ* 32 (4), S. 725–730.

Matsuda, M.; Kashiwase, K.; Sudo, Y. (2012): Agent Oriented Construction of a Digital Factory for Validation of a Production Scenario. In: *Procedia CIRP* 3, S. 115–120. DOI: 10.1016/j.procir.2012.07.021.

Monostori, László (2014): Cyber-physical Production Systems. Roots, Expectations and R&D Challenges. In: *Procedia CIRP* 17, S. 9–13. DOI: 10.1016/j.procir.2014.03.115.

Peffers, Ken; Tuunanen, Tuure; Rothenberger, Marcus A.; Chatterjee, Samir (2007): A Design Science Research Methodology for Information Systems Research. In: *Journal of Management Information Systems* 24 (3), S. 45–77. DOI: 10.2753/MIS0742-1222240302.

Picot, Arnold; Reichwald, Ralf; Wigand, Rolf T. (2003): Die grenzenlose Unternehmung. Information, Organisation und Management ; Lehrbuch zur Unternehmensführung im Informationszeitalter. 5., aktualisierte Aufl. Wiesbaden: Gabler (Gabler-Lehrbuch).

Pindyck, Robert; Rubinfeld, Daniel (2009): Mikroökonomie. 7., aktualisierte Aufl. [der amerikan. Aufl.]. München: Pearson Studium (Wi - Wirtschaft).

Rand, William; Rust, Roland T. (2011): Agent-based modeling in marketing. Guidelines for rigor. In: *International Journal of Research in Marketing* 28 (3), S. 181–193. DOI: 10.1016/j.ijresmar.2011.04.002.

Sahin, Cenk; Demirtas, Melek; Erol, Rizvan; Baykasoğlu, Adil; Kaplanoğlu, Vahit (2015): A multi-agent-based approach to dynamic scheduling with flexible processing capabilities. In: *J Intell Manuf. DOI:* 10.1007/s10845-015-1069-x.

Schenkel, Peter (2015): Elektronische Dienstleistungsmarktplätze - Prozessmodell, IT-Architektur und Demonstration.

Schwickert, Axel C.; Pfeiffer, Ellen (2000): Elektronische Marktplätze : Formen, Beteiligte, Zutrittsbarrieren. In: *Arbeitspapiere WI.* Online at http://geb.uni-giessen.de/geb/volltexte/2004/1573/pdf/Apap_WI_2000_05.pdf, zuletzt geprüft am 22.08.2016.

Shoham, Yoav (1993): Agent-oriented programming. In: *Artificial Intelligence* 60 (1), S. 51–92. DOI: 10.1016/0004-3702(93)90034-9.

Theuer, Hanna; Gronau, Norbert; Lass, Sander (2013): The Impact of Autonomy on Lean Manufacturing Systems. In: Américo Azevedo (Hg.): Advances in sustainable and competitive manufacturing systems. 23rd International Conference on Flexible Automation and Intelligent Manufacturing ; [FAIM 2013 ; Porto, Portugal ; proceedings]. Cham: Springer (Lecture Notes in Mechanical Engineering), S. 1413–1423.

Tsvetovatyy, Gini; Mobasher, Bamshad; Ski, Zbigniew Wieckow; Ski, Wieckow (1997): Magma an agent-based virtual market for electronic commerce. In: *Applied Artificial Intelligence* 11 (6), S. 501–523. DOI: 10.1080/088395197118046.

Woll, A.; Vogl, G.; Weigert, M. M. (2000): Wirtschaftslexikon. 9., völlig überarb. und erw. Aufl. München: Oldenbourg.

Wong, T. N.; Leung, C. W.; Mak, K. L.; Fung, R. Y. K. (2006): An agent-based negotiation approach to integrate process planning and scheduling. In: *International Journal of Production Research* 44 (7), S. 1331–1351. DOI: 10.1080/00207540500409723.

Wooldridge, Michael (2009): An introduction to multiagent systems. 2. ed. Chichester: Wiley.