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Mastering Complexity with Autonomous Production Processes

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Abstract

For the consolidation and improvement of a companies market position it is necessary to master the increased complexity of production processes with suitable methods. This paper will examine whether and how far autonomous production processes are suitable to master the complexity of production processes. The paper starts with an introduction of the problem definition followed by an explanation of theoretical foundations of complexity in production, autonomy and cyber-physical production systems. In addition, selected already existing methods to master complexity are presented. The second part of the paper starts with an introduction into measuring the degree of autonomy in production processes which is the basis for the following simulation-based analysis. Afterwards, the simulation environment is presented. The third chapter is about the experimental analysis of the presented research question. Therefor, the experimental set up and the implementation are presented. The paper ends with an outlook on further evaluation activities.

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1. Problem definition

Changing market conditions, variable customer demands and growing customer requirements lead to an increasing complexity in production processes. Additionally, they are some reasons for manufacturing companies to create flexible and adaptable processes to fulfil the customer demands in a high quality. Companies have to determine the best grade of complexity for their specific processes. On the one hand side they have to fulfil the customer demands, on the other hand side they must be able to handle the complexity in an adequate manner. There are several methods for dealing with the named challenges: lean production, advanced software systems and decentralization of decision making with the help of intelligent autonomous technologies for instance. While lean production focus on the elimination on non-value adding processes, software systems may assist the process by the automatisation of decision making due to algorithms. With the help of technological or human based autonomy it is possible for production objects to proceed the information making and decision execution on their own. This decentralisation of production control seems to be an adequate method to deal with the current requirements on production processes. This paper will examine whether and how far autonomous production processes are suitable to master the complexity of production processes. Section 2 provides an introduction into the underlaying theoretical foundation, section 3 describes the process evaluation for the analysis of the benefit of autonomy to handle complex production systems. The paper ends with an outlook on further research activities.

2. Theoretical Foundation

This first section provides a theoretical foundation. Firstly, fundamentals of complexity in production systems are presented, followed by a brief introduction into cyber-physical systems. The section ends with a presentation of autonomous production systems.

2.1. Complexity in Production Systems

As there are several different disciplines using the term of complexity, there is no consistent definition of the term. Exemplarily, the definitions of complexity in systems theory, cybernetics, and computational science are presented in this paper. Systems theory defines complexity as a ratio of elements of the systems and their connecting relations [1]. Cybernetics uses the variety for measurement. Variety describes the amount of possible and distinguishable states a system can hold [2]. Computational Sciences use complexity for the analysis of time and space requirement of algorithms.Used methods are Big O and turing machines for example [3].

Also, various classes of complexity can be distinguished. For production systems, the most relevant are product, pro-

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cess, coordination, and environmental complexity. As there are impacts between the different classes of complexity, they may not be considered separately but in a correlated way. For instance, the product complexity has a direct influence on the processes produced in and thereby the belonging process complexity [4,5].

Complexity in production processes has increased during the last years. Reasons for this are among others an increasing diversity of variants caused by individual and heterogenous customer demands, changed requests of piece items down to one piece production, technological innovation, decreasing cycle of innovation, short-time lifecycle, increasing international sales and procurement market, differences of planning and decision systems of cooperating companies as well as a increasing connectivity caused by the reduction of vertical range of manufacture [6–8]

The named facts clarify that complexity as itself is not bad and has to has to be avoided. Instead, complexity may be a basis for the successful fulfilment of customer demands and the directly linked business activity. Nevertheless, complexity has risks e. g. The incapability of acting or increasing costs. It is necessary to determine the right dimension of complexity. In a next step, adequate methods have to be selected and applied to these dimensions. Basic categories of those methods are the avoidance, the reduction and the mastering of complexity[7].

The underlying research work for this paper focuses on the mastering of complexity. The applicability of an autonomous production control for mastering complexity is determined. It is mandatory to make quantifiable complexity as well as autonomy. Section 3 presents appropriate approaches.

2.2. Cyber-Physical Production Systems

LEE provides a definition of cyber-physical systems that has a general characterisation [9]:

> ”Cyber-Physical Systems (CPS) are integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa.”

Therefore, CPS combine software based information processing and interaction with the surrounding physical environment. Due to this interaction, embedded systems and their linkage realises tasks of control and monitoring as intelligent control loops [9].

Additionally, ACATEC describes CPS as software intensive and embedded systems and integrated application that realise the usage of data and service anywhere in the world. This is realised with the help of sensors, actors and local information processing in combination with a comprehensive networking [10]. Dedicated utilisation interfaces and various integration in digital networks allow a wide spreading integration of functions [10,11].

The term of cyber-physical production systems (CPPS) often finds application in the context of CPS-based automation [12]. Existing plant components, as well as whole production facilities, are combined to CPPS. This implies that a CPPS is the combination of several, initially independent CPS to a larger production system. A high degree of networking of elements characterises this production system. It represents an autonomous and intelligent production unit [13].

2.3. Autonomous Production Systems

Various fields of live and science e. g. politics, automobile industry and psychology use the term autonomy to describe the independence of field specific objects and instances. Autonomous production systems are characterised by the existence of several decentral actors that control the systems by their own. These actors can be part of a cyber-physical system. They need to fulfil at least three characteristics: information processing, decision making and decision execution [14].

When regarding autonomy in production processes in literature, there is a clear focus on technology [15,16]. But in due consideration the three named characteristics, it turns out that there is more needed than technology to enable autonomy in production. According to the etymology of the term autonomy (it is defined as the capacity of a rational individual to make an informed, un-coerced decision [17]) an other possibility to create an autonomous controlled production is autonomy by human action and organisation. Both (hardware (machines, workpieces, carriers or conveyors) and human) are able to proceed intelligently, either independently or due to a combination of them. The degree of combination may vary from a high interaction to a nonexistent one [18].

Information processing includes data input, data storage and data aggregation. Relevant data has to be tagged to the production object. Therefore special technology is necessary [14]. An common examples for such an technology is Radio Frequently Identification (RFID) [19]. Decision making combines the aiming system with predefined rules as well as the communication with further production objects. For the decision execution the communication of different production objects as well as the capability of a production objects to performance alternative processes is necessary [14]. Even though humans have the names characteristics ”integrated”, they might require the availability of information for an adequate decision making. These information might be provided by software terminals that are placed directly at the shop floor for example. Autonomy in production systems gained in importance during the last years. Autonomous production objects are one core capability for Industrie 4.0 (a term mainly used in Germany) or Smart Production [20].

3. Process Evaluation

This section firstly describes methods for measuring autonomy and complexity in production systems as well as the determination of key figures followed by a short conception of the used simulation environment.

3.1. Measuring Autonomy in Production Systems

To analyse autonomous production systems, the authors of this contribution developed a method that enables a measurement of autonomy of production systems and thereby gives a basis for the evaluation and comparison of various systems or their set ups [21,22]. The core element of this method is the

Autonomy Index AI that puts into relation autonomous part of the considered value stream to the whole one. Other parts of the methods are an Extended Value Stream Method that allows the consideration of relevant autonomous information in the modelling of production processes and a Data Dictionary for the documentation of further relevant process and product information of the autonomous production system [23].

The Autonomy Index specifies the degree of autonomy used in the production process. The term was chosen following the term Lean Index used in Toyotas Value Stream Design [24]. While defining the index the basis for the comparison had to be determined. There are various possibilities, e. g.:

- Number of autonomous processes : number of all processes
- Number of autonomous process steps : number of all process steps
- Autonomous controlled process time : total cycle time
- Autonomous quantity of data : total quantity of data

The practical execution has shown that the number of autonomous process steps is the most suitable of the named possibilities. Relevant data can be accorded in laboratory and even on site in the shop floor without an extensive time- and cost-consuming experimental procedures. Autonomy in production systems cant just be achieved by hardware autonomy but also by autonomy of human[18]. These enablers that (also called levels) of autonomy can be considered by means of Autonomy Index. Due to its high importance software is considered as a third enabler. Besides two additional key figures were defined to characterise the autonomous system more detailed: the Interaction Index II_x and the Communication Index $CI_x y$. In the following the three indices are described formally and mathematical. Their mathematical relationship is elaborated. The Interaction Index II_x describes the proportion of autonomous process steps $PS_{aut,x}$ executed with the help of communication of actors within the same level x to the total amount of process steps $PS_{all,x}$ in level x. The Communication Index CI_{xy} describes the proportion of autonomous process steps $PS_{aut,x,y}$executed with the help of communication of actors of level x to actors of level y to the total amount of process steps $PS_{all,x,y}$ that are executed with the help of communication of actors in level x to actors in level y. CI_x describes the proportion of autonomous process steps $PS_{aut,x}$ executed with the help of communication of actors of level x to actors of all other levels to the total amount of process steps PSall,x that are executed with the help of communication of actors in level x to actors in all other levels. The Autonomy Index AI describes the proportion of autonomous process steps to the total amount of process steps [25].

3.2. Measuring Complexity in Production Systems

A key objective of the operationalisation of complexity is the possibility to gain comparable processes respectively process scenarios and thereby enable a valuation of methods for the reduction and mastering of complexity. Challenges are especially different interdependencies and interactions within the process, interdependencies of parameters of the object of reflection and the differential of real und subjective perceived complexity. There is the need for setting up objective and measurable criteria. Two possible approaches are both the valuation of complexity by entropy and the valuation by parametrisation. The term entropy is used in technical as well as in social sciences. The respective definitions are matched to the object of reflection. Computational Sciences defines entropy as a measure of randomness that is inherent to a signal a random result. The field of mathematics defines conditional entropy as a measure of uncertainly of the value of a random variable after knowing the value of a second variable. Social Sciences use entropy to define an information lack. Its size measures the effort for the removal. Approaches for the measuring of complexity by entropy originate from SHANNON and FRIZELLE/WOODSTOCK for instance. Shannons concept is based on the probability of the change between different conditions of a system. He uses Markoff graphs [26]. Frizelle/Woodstock determine complexity by diversity and the uncertainly of information [27]. Approaches for measuring complexity by a parametrisation origin, among others, from WOOD, MALIK, COSTA et al and PHILLIP/BÖSE/WINDT. Wood undertakes a differentiation of task, coordination and dynamic complexity [28]. Malik differences real and subjective reality that is measure with the help of variety [2]. Costa et al. describe a complexity vector that takes into account several factors. The vector allows a comparison on an ordinal scale. The change of a vector due to a transformation can be analysed by a comparison of both vectors. The usage of a transformation matrix allows the analysis of dependencies [29]. PHILLIP/BÖSE/WINDT developed a complexity cube that considers time, system and organisational complexity. Time complexity distinguished static and dynamic complexity. While within the first one the system is regarded at a defined time, the dynamic complexity considers the system and its changes over a period. Organisational complexity differences process complexity (the amount of different emphasis of process flow) and structural complexity (the amount and manifestation of system elements and their belonging relations). The third view - system complexity - differences internal and external complexity. Internal complexity considers organisation complexity within the system; external complexity considers organisation complexity outside of the system. It is possible to build relationships with between the three views [30]. This enables an extensive consideration. Slicing and dicing enable detailed analysis similar to those of Online Analytical Processing (OLAP).

The research work that underlies this paper uses a complexity vector $\vec{c}$ that consider elements of the internal complexity cube. As the research focus on production processes, the external complexity is not in the focus on consideration.

$$\vec{c} = \begin{pmatrix} amount\ of\ different\ processes\ per\ machine \\ amount\ of\ working\ stations \\ order\ sequence \\ variation\ of\ amount\ of\ available\ working\ stations \end{pmatrix}$$

3.3. Determination of Key Figures

For the evaluation of processes and assessment of alternative scenarios, it is necessary to define one or several target figures. These target figures have to be measurable in the process. For the evaluation of production processes logistic key figures, such as the adherence to delivery dates and the lead time, have a high importance as they allow the consideration of process performance. Therefore, the authors use a vector $\vec{e}_{process,is}$ with four logistic key figures to evaluate the process scenarios. A comparison of $\vec{e}_{process,is}$ with the target values of the four used key figures (implementier in $\vec{e}_{process,target}$ results in a third vector $\vec{e}_{process,aim}$

By the usage of a weighting vector $\vec{e}_{weight}$, a single key figure is created [31] The weights can be varify but they should be equal at least in one test series. The zum of all weight have to be 1.

$$t = \vec{e}_{process,aim} * \vec{e}_{weight} = \begin{pmatrix} adherence\ to\ delivery\ dates \\ lead\ time \\ utilisation \\ work\ in\ Progress \end{pmatrix} \begin{pmatrix} weight_1 \\ weight_2 \\ weight_3 \\ weight_4 \end{pmatrix}$$

3.4. Hybrid Simulation Environment

The analysis of the effects of autonomy on complexity uses a simulation environment provided by the Lab of Anwendungszentrum Industrie 4.0 at Potsdam University. The hybrid simulation environment as a combination of software simulation and physical model factory enables a configuration of all production objects of the simulation environment for different levels of decentralised production control, e. g. as cyber-physical systems (CPS) in variable extent. The term production objects comprise elements of a production system like machines, working stations of plant components as well as software systems and human workers. All of them are available in virtual or real nature which is freely combinable within the runtime environment of this simulation platform. This allows modelling and analysis of several production processes as well as various scenarios with different levels of autonomy [21,32]. Though, this tool enables a simulation based approach for exploration and validation. Fig. 1 shows a part of the Anwendungszentrum Industrie 4.0 in Potsdam.

Fig. 1. Hybrid Simulation Environment in Anwendungszentrum Industrie 4.0

4. Experimental Analysis

This section presents the experimental analysis in Anwendungszentrum Industrie 4.0 at Potsdam. It firstly describes the used process in an experimental set up followed by a description of the implementation.

4.1. Experimental Set Up

For a first experiment, a production scenario that consist of five working stations is set up in the simulation environment. It considers different kinds of working stations such as a processing centre for grinding, a robot that engraves the products and the manual workplaces. The grinding centre is integrated in duplicate. the simulation environment has a high flexibility. Every process can be simulated as autonomous or central controlled. Fig. 2 pictures a conceptual drawing of the scenario. This scenario enables the consideration of several process elements that are relevant for autonomous production control such as the selection of parallel working stations and the integration of human and robotics.

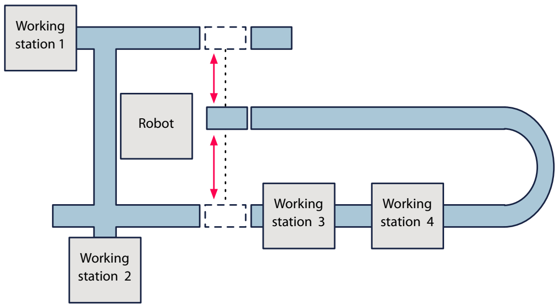

Fig. 2. Conceptual Drawing of Experimental Set up in the Simulation Environment

4.2. Implementation

After defining and selecting different scenarios, the complexity vectors according to subsection 3.2 are defined and the simulation environment is configured to provide the relevant key figures or rather their components. Afterwards, an overall plan for the simulation is created. This plan includes e. g. the simulation time and disturbances. The plan ensures that the scenarios are simulated consistent and comparable. The scenarios and their simulation results are documented and analysed. Used methods are inter alia: 3D-plots for the graphical analysis of correlations and transformation matrix for the analysis of dependencies. The test series will consist of at least three different scenarios with each a different degree of autonomy: one with no autonomy, one with full autonom and one with a degree of autonomy that is in between the two others. Degending on the results, additional scenarios will be set up and analysed.

5. Outlook and Discussion

At present, the described process in implemented in the simulation environment. First simulation runs were performed. Although there are already some first data existing it is still necessary to customise and expand the data collection to get reliable statements. Although the described analysis is well reflected, it is possible that there is the need to implement changes and complements. Additional, there is still the challenge how to deal with dependencies of the degree of autonomy and complexity. There might be the case, that a change in autonomy influence one or more key figures in the complexity vector. This falsifies the results. One option to deal with this is a correction factor.

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