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Symbiosis of Changeable and Virtual Production – The Emperor's New Clothes or Key Factor for Future Success?

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Abstract

In today's globalized markets, the continuous pressure to perform at high levels is well perceivable in the companies' every day business. The concepts of both a changeable and a virtual production, also known as the digital factory, claim to be of great importance when preparing the manufacturing and assembly systems for future challenges. In this paper, the characteristics of both concepts are pointed out. It is analyzed that the digital factory, as it is currently designed and implemented, is suitable for supporting the objective of changeability. However, some drawbacks still exist today, e.g. a bidirectional connection between centralized and decentralized planning and implementation is missing. Identifying the necessities of future research activities, the closer linkage of the concept of changeability and the digital factory in the future is said to be one of the key factors for economic success.

Keywords

Changeability, Digital Factory

1 INTRODUCTION

The last decade has brought forth enormous changes in world economy. Markets in industrial countries have reached a level of maturity, where quality, technical superiority and short delivery lead times of products have become mere prerequisites for market success. Companies today can only compete if they offer products and services that meet the customer's individual needs.

This has lead to an increasing number of products, product variants and configurations offered. Concepts such as mass customization and individualization promise the creation of unique items for nearly every customer. Decreasing product lifecycles leave only short and transient windows of opportunity for companies to profitably produce and sell a particular product or service using a given value chain. Corporate managements have had to accept the fact that market forecasts have turned more complex and that rapid changes in the marketplace cannot be controlled. At the same time, globalization has intensified the worldwide competition and imposed a permanently growing pressure on production costs.

All of these developments create a situation often referred to as a turbulent environment (see figure 1), which is characterized by high complexity and dynamics [1]. The unpredictability of market changes, the growing product complexity and continuous pressure on production costs force companies to develop the ability to respond and adapt to change quickly and effectively.

In recent times, a variety of concepts for coping with these challenges has been discussed in the domain of production engineering. Two prominent ones are 'changeability' and the so-called 'digital factory'. The latter one is a set of computer aided methods and tools dedicated to providing a virtual model of the real production that can be used for planning, experimenting and implementation. The 'digital factory' enables companies to create a virtual production already in the process of product development. It allows an efficient planning and optimisation of production facilities along the whole product lifecycle. The paradigm of changeability describes concepts and methods to facilitate the adaptation of production to new, unforeseen situations. In contrast to the digital factory, which is focused on the lifecycle of the product, changeability mainly addresses the lifecycle of the respective production systems.

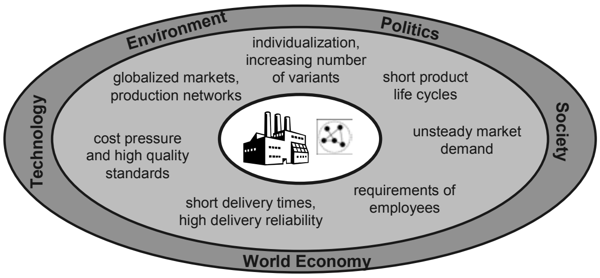

Figure 1. Turbulent environment [2]

In this paper, we will show that the integration of changeable and virtual production is of particular importance for future economic success in manufacturing. Furthermore, we will point out the most prominent drawbacks in the symbiosis of changeable and virtual production today. We identify how to support the concept of changeability by means of the digital factory and we derive important areas of future research.

The paper is organized as follows: In the next part (chapter 2), the concepts of changeability and digital factory are introduced briefly. Then the characteristics and requirements of a changeable production are described in chapter 3. Afterwards we analyze, to which extent the objectives of changeable production can be supported through today's digital factory approaches. In chapter 5 possible future developments are outlined. It is shown how the linkage between changeable and virtual production can be intensified and that by means of a symbiosis of changeable and virtual production the competitive position of manufacturing companies can be strengthened. Finally, the paper is summarized in chapter 6.

2 CHANGEABLE AND DIGITAL FACTORY TODAY

2.1 Changeable production systems

Changeability as the 'ability to change' and to adapt the company to new circumstances describes a concept which is popular especially in German literature. Although the concept of changeability is widely accepted, the notion is not yet defined in a uniform way. Furthermore, many similar terms such as agility, reconfigurability or flexibility seem to refer to almost the same idea. Especially flexibility has been defined innumerable times and can include, depending on the specific definition, all the terms mentioned above [3]. In the following paragraphs the differences between those concepts are pointed out.

2.1.1 Reconfigurability

The concept of reconfigurability centres the development of modular hardware and software to adapt to market demands [4]. By integrating or removing single functional elements, the manufacturing system may be adjusted to exact capacity and technology requirements. The concept is focused on technical aspects of machining and assembly, whereas organizational issues are not considered. Hence, reconfigurability is limited to single workstations or production cells [2, 5].

2.1.2 Flexibility

Different literature reviews show that despite the fact that the work on flexibility is vast and articulated, a certain ambiguity in the definitions persists [3, 6]. Slack introduced flexibility of a system as a measure for the range of reachable states and the time and cost required for moving from one state to another [7]. The cost and time necessary for making a change (i.e. shifting to another state) are the 'friction' elements of the flexibility of a system. If this friction is removed and all constraints of time and cost are relaxed, then almost any degree of change is possible. Slack also states that any boundary restricting the range of 'flexibility' has to be arbitrary. But most of the definitions on manufacturing flexibility describe an operation system which is able to alter its in- or output without changing the system itself. Consequently, a flexible system is built for a set of reachable states, which are predefined during the engineering and design phase.

2.1.3 Agility

A broader approach represents agile manufacturing. An agile manufacturing system aims 'to meet the changing market requirements by suitable alliances based on core-competencies, by organizing to manage and change uncertainty, and by leveraging people and information' [8, 9]. Agile manufacturing is an approach focused on supporting the whole enterprise to reach agility. The suggested measures are a synthesis of well-known techniques and methods such as lean manufacturing, TQM or Business Process Engineering [10]. Also flexibility and reconfigurability are part of the agile manufacturing 'toolbox'. Agility describes the strategic ability of the whole company or a virtual enterprise to cope with a turbulent environment [2, 5].

2.1.4 Changeability

Changeability focuses the whole production system, that is the management system, the operation system and the information system linking the first two subsystems. It is more than reconfigurability because it is not limited to hardware and software. In contrast to flexible systems, changeable ones are capable of varying their own structure. That meets the fact of the unpredictability of change, because the set of reachable states is not limited a priori. Changeability considers the shift of the possible range of states with minimum costs and time as shown in figure 2.

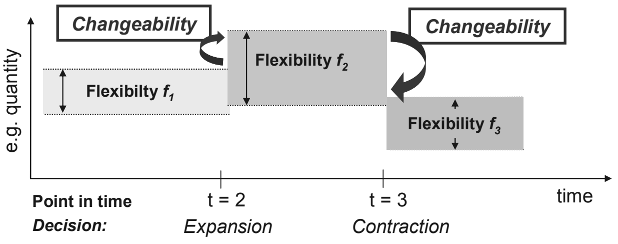

Figure 2. Difference between changeability and flexibility

The objectives of agile manufacturing are valid also for changeable systems, but they are too widespread on different functions within the enterprise. Unlike agile manufacturing, changeability cannot be achieved by combining well known techniques only, which could be very costly. New production system design principles have to be applied and many supporting tools such as process planning need to be enhanced to meet the requirements of a changeable production system [11]. The causes of changes can range from minor fluctuations in production volume to major shifts in the production program.

2.2 Digital Factory

Initiated by the increasing computer support in product development, a variety of tools and simulation techniques have been introduced to the domain of production planning throughout the last two decades. With 3D-CAD as one of the main enabling technologies, companies started in the late 1980s to create computer models of entities in their production. Tools like robotic offline-simulation or discrete event simulation provided the possibility to preview and to evaluate dedicated aspects of a production system. Driven by the idea to interlink product development and production planning by means of digital tools and a common data basis, these tools were permanently being enhanced in functionality. Their integration and exchangeability of data became important issues. This way, a diversity of computer aided tools for production planning have evolved throughout the 1990s, nowadays referred to by the commonly known notion of the digital factory. This term comprises not only software tools but also the staff involved and the processes which are necessary for creating the virtual and real production respectively. The digital factory can be seen as a set of methods, tools and user interfaces, whose focus and applicability range from enterprise-wide aspects to plants, production systems and processes [12, 13].

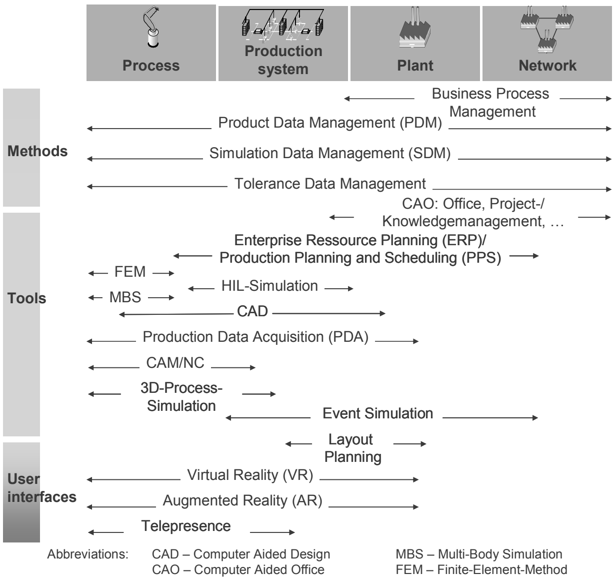

Figure 3. Tools of the Digital Factory

The approaches in this field have reached a level of maturity, where the goal of an integrated, experimental planning, evaluation and controlling of production by means of digital models has become realizable [14]. The idea of the digital factory has become very popular also in industry in the last few years. Considerable effort has been made to implement software and to train people. In particular the OEM in the automotive industry have announced special programs to support the whole process of manufacturing (product development, engineering and production) by dedicated tools of the digital factory.

More than one decade ago, the concept of CIM attracted a similar attention. A lot of money was spent without realizing the vision of this concept. Therefore it is legitimate to question the relevance of the digital factory and to analyze its impact on other frameworks which may strengthen the competitive position of manufacturing companies. As described before, changeability is one of those concepts. In the next sections we derive the key characteristics of changeable production and analyze how the digital factory supports the companies in getting 'changeable' today. Existing drawbacks are outlined and used to derive necessary future research and development.

3 CHARACTERISTICS OF CHANGEABLE PRODUCTION

In order to analyze the impact of the digital factory on gaining changeability today and in the future, it is necessary to identify the key characteristics of a changeable production. This way, the support required from digital tools may be derived when striving for changeability. Based on our research experience and on projects with industry partners, we state the following issues to be characteristic for changeable production systems.

(3.1) Frequent changeover and reorganization of production

The reorganization of the manufacturing system can be compared to a technical changeover. Each of the states of the production system represent a specific 'target product' characterized by a unique production function which determines how a set of input factors is transformed to a set of output factors. Besides a technological output, this production function describes a specific combination of the production objectives quality, cost and time. In a changeable production, many changeovers from one state to another take place.

On the one hand there are external factors (need for changeovers) that result from the high turbulences described in the first section of this paper. Product lifecycles are permanently decreasing as the market requires smaller total lot sizes (i.e. production of a specific output at a certain combination of costs, quality and time). This development is driven by customers who ask for immediate fulfilment of their needs or otherwise would not buy the produced output. Consequently, small lot sizes and frequent occurrence of changeovers assure that the production quickly follows the varying requirements.

On the other hand, there are internal factors (capability to changeover) that describe all the activities that have been undertaken to introduce more changeable technical and organizational structures. By reducing the time and cost of a changeover, it becomes economically reasonable to adjust the production system to the optimal operating point more often.

(3.2) Adaptation to unplanned and unexpected situations

Corporate managements have to accept the fact that rapid changes in the market cannot be controlled. The unpredictability of change is a major factor limiting a company's capability to respond effectively in a previously planned matter.

Hence it is not sufficient to design a production system which can operate at a maybe high, but still limited, previously planned number of discrete states. Changeable production systems are characterized by the capability to modify their own structure 'easily' in a way that has not been planned before. This means, that a system has to offer a degree of freedom which facilitates the re-planning exactly when needed, whereas the planning during the design phase is always limited to somehow expected situations. Thus, a changeable production needs to include an undirected potential to adapt even to unforeseen situations.

(3.3) Relevance of changeability at all levels of production

Changeability describes the capability to adapt the production system to new situations. The production system itself may be formalized by means of a process model representing all the processes necessary for the technical order processing, the resources assigned to those processes and the dependencies between the single processes. Consequently, the change of a production system may become manifest in the modification of a specific process and its resources or in the variation of the links between the processes.

Thus, changeability can be gained if resources are capable of being modified easily to fit into a new process configuration, e.g. by switching the control hard- and software or by varying the feeding or the work space. It is more difficult to describe how changeability can be achieved on the process level since production processes can be particularized on different levels such as production cells, factories or even networks. Hence, the concept of changeability needs to be considered on different planning levels and to include technical and organizational aspects, such as logistics or information flow. The objective of designing a changeable system is always to reduce the loss after modifications in such a way that a fast and almost binary ramp-up (see figure 4) can be achieved.

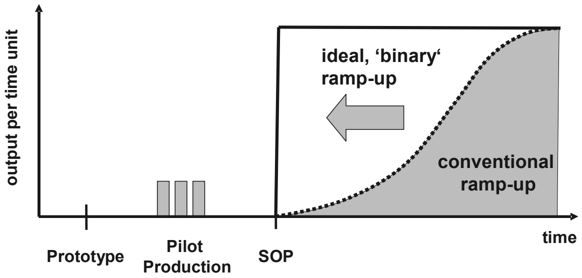

Figure 4. Binary ramp-up

(3.4) Central and decentralized planning and implementation of changeability

The characteristics of both central and decentralized planning and implementation of changeability are closely linked to what we described before. Different authors showed that a production system may be adapted to new situations efficiently not only by modifying single processes but by combining several processes in the right way (e.g. [15]). Consequently, a central planning is needed to avoid local (and costly) optimization and to strive for a global improvement. However, different levels of a production system require a varying granularity of planning. It is well accepted that a single central planning unit cannot be aware of all unique characteristics of each process, thus local (decentralized) planning is also needed. The full economic potential of changeability can be reached by the combination of global and local planning approaches.

4 GAINING CHANGEABILITY THROUGH DIGITAL FACTORY APPROACHES?

Multiple requirements on both an organizational and an operative level have to be met in the strive for changeability. A thorough analysis is necessary to identify the extent to which the fulfilment of these needs can be supported through today's digital factory approaches. The concept of the digital factory and its current implementation in industry supports mainly product and process design. From the perspective of production engineering, the central enhancements gained through the digital factory can be summarized as follows:

- Efficient and fast planning: The tools of the digital factory allow for efficient collaborative work on a consistent data base. Also work flows and decision processes are digitally supported and sped up. Planning tasks on several levels are accelerated by dedicated tools (figure 3), which often share a common database. The data integration however only embraces the planning staff and is unidirectional, excluding the operational units with their ability to assess and optimize.

- Virtual ramp-up decoupled from real factory: Based on digital models, production and assembly systems can be configured and programmed afar from the real machinery. This way, ramp-up efforts can be shifted into an earlier phase such that the overall process is sped up and it also helps to minimize non-productive times related to frequent change. Virtual ramp-up is based on a top-down approach by which reconfiguration is shifted from reality towards models.
- Reusability: Once a first instance of the digital factory has been created, the reuse and adaptation of previously implemented production concepts, factory models and configurations becomes theoretically possible. At the current stage in industry however, the digital results of planning are highly dispersed over a variety of information systems without being organized by a consistent meta-modelling concept. Therefore reusability in practice is restricted to a “copy and paste” of old planning data or the reuse of CAD-models.
- Evaluation of discrete alternative concepts: Using simulation techniques like e.g. event or dedicated process simulations, the impact of both alternative production approaches as well as changes on current systems can be evaluated in a detailed manner. E.g. a whole body in white assembly line can be virtually simulated in both discrete event simulation and 3D-simulation. On the one hand, such simulations can be used to validate and optimize the current solution in terms of e.g. line balancing. On the other hand they are a good means to evaluate different conceptual designs against each other. However this requires manual modelling of the alternatives to be compared.

As discussed in the previous section, changeability requires the ability to frequently changeover (3.1), to adapt to unplanned situations (3.2), to support planning on all levels of a production system (3.3) and to combine both centralized and decentralized action (3.4). In the following paragraph, we will analyze to which extent the digital factory as it is designed and implemented today addresses these requirements.

Frequent changeovers (3.1) are facilitated by the digital factory in terms of allowing fast and efficient planning as well as a virtual ramp-up. Reducing cost and time required for preparing and implementing a changeover, companies are enabled to reorganize their production more often. Virtual ramp-ups decoupled from the real factory strongly contributed to the vision of a digital ramp-up, where production down-time and financial losses due to introduction of a new product or production process are minimized (figure 4).

The ability to adapt to unplanned situations (3.2) is a characteristic of changeable systems. Hence, the design and evaluation of such systems is focused on the potential that is inherent in a production system. On the other hand, the digital factory is aimed on planning and detailing a discrete solution to a complex manufacturing problem. When it comes to evaluation, the digital factory therefore only offers the possibility to manually detail several discrete alternative solutions and compare them against each other. Consequently, the digital factory can help to evaluate known alternatives, but it provides little aides for finding them.

Today’s off-the-shelf product suites, e.g. offered by Delmia or UGS/Tecnomatix, include several dedicated tools supporting planning tasks across all different levels of production (compare 3.3) from planning of production lines and logistics simulation down to the process level at a single NC machine or welding robot. Those packages are indeed powerful and suitable for the applications in the area of large producing companies, such as automotive OEMs. For those tasks, which are not covered by standard functionality, for instance production network planning and configuration or simulation of laser beam welding, other tools are available or under development.

Although a richness of tools exists for nearly every planning task on every level of production, the integration between the tools of the digital factory is rigid and unidirectional (i.e. top-down from initial rough to detailed planning). However, gaining the full potential of changeability requires a strong linkage between centralized and decentralized measures (compare 3.4). The paradigm of digital factory is a central one and it presumes known planning cycles. Those cycles can be found e.g. in automotive industry where reorganizations of production lines are closely linked to the introduction of new car models and the planning tasks strongly resemble each other. The digital factory is a powerful tool whenever a central group, in charge of all engineering and planning decisions is planning ahead, while operational units are merely implementing central directives. The optimizations that are done locally during the implementation are therefore not documented in the digital factory and are thus also not available in following planning cycles.

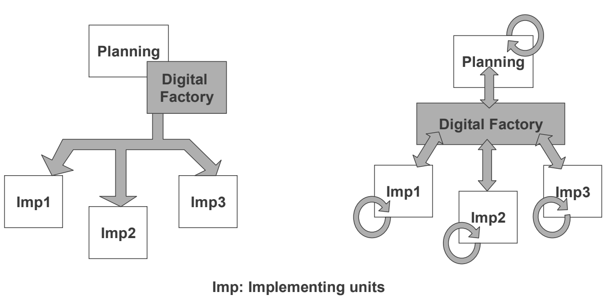

Figure 5. Centralized vs. decentralized digital factory

Summarizing this analysis, the digital factory matches some of the characteristics of changeable production systems but leaves an immense potential unused. Currently, frequent changeovers as well as planning tasks on all levels of production are supported by adequate tools and methods. In contrast, the adaptation to unplanned situations and the integration of centralized and decentralized planning are merely addressed by the digital factory of today.

5 FUTURE CHALLENGES AND RESEARCH

As it can be seen from the analysis in section 4, digital factory approaches can provide support for changeability in several aspects, mainly by increasing efficiency and effectiveness of planning and implementation cycles. However in both the conception and the implementation of today's digital factory there are conflicts with the paradigm of changeability such that a major part of the potential in supporting change by digital tools remains unused.

The most important conflict can be found between the central, top-down planning approach of the digital factory and the fact that full potential of changeability can only be gained by involving and interlinking centralized and decentralized action. The digital factory of today separates planning from implementation and thus only supports central planning followed by a decentralized implementation of planning results by employees on the shop floor.

In order to fully support changeability, the digital factory needs to be decentralized and a bidirectional linkage covering also the reverse direction, i.e. from decentralized operative to central planning units needs to be created (compare figure 4). This means extending access to the digital factory also to people in operative units and on the shop floor respectively and making their expertise and problem-solving potential usable in the process of reorganization.

The digital factory of the future should therefore no longer be a tool exclusively used by and localized in central planning divisions but it should become an ambient medium connecting and supporting both centralized and decentralized units when it comes to change. There are various technologies either already available or currently upcoming in the area of the digital factory which can contribute to realizing this vision. Four central questions will need to be addressed by the future digital factory.

(1) How does global planning know, what local units look alike?

Today, most production facilities are digitally planned and documented only during their planning and construction phase. However in times of constantly decreasing product-life-cycles, production systems have to be reconfigured and redesigned several times along their life-cycle. Therefore, global planning units need to be provided with a consistent and up to date view of local facilities, even though these are prone to permanent adaptation of the production system. With increasing number of changes, the manual update of the digital models is no longer viable. On the one hand, approaches like 3D-reconstruction using laser range scanners are a good way for creating detailed models ex post. On the other hand, Augmented Reality can help to match current real environment with the computer-generated models. Nevertheless, these approaches are costly and time-consuming and can capture only the current state of the production system, that is to say they provide just snapshots.

In the future, efficient mechanisms need to found to ensure that models, once initially created are permanently updated and matched with reality. Therefore, sensors for identification, localization, mapping of status and shape of objects need to be integrated in future production environments and, even more important, methods for automatic aggregation of these data into consistent and up to date high-level models of the production environments are necessary.

(2) How can global planning be communicated and jointly optimized together with the local units?

From a global perspective, production planning needs to be based on latest data about the product, the current state of the shop floor, including machine configurations, availabilities, supplies and logistics. Global decisions such as the temporary allocation of production volumes in a network environment or the selection of currently available suppliers have direct impact on local units and their processes, respectively.

Especially when producing highly varying products, process planning can best be supported by knowledge-based approaches that systematically explore and optimize valid process configurations based on both product information and the production system's current state. While these approaches are applicable to a single production area today, the future challenge will be the integration of a company's multiple plants. It will also be an important issue to find ways for including potential subcontractors or outsourcing partners used as an elongated workbench into the planning.

One level beneath, considering a single production site, a permanent adaptation of production processes and a continuous, bidirectional communication chain from central planning units to the shop-floor and vice versa is an important prerequisite for changeability. Integrating shop floor workplaces with digital process planning, e.g. by means of multimedia terminals or in the future also Augmented Reality guidance, allows for an efficient top-down communication of process plans. These systems also need to offer the possibility of user input on the shop floor, for instance to modify or evaluate central planning decisions. Consequently, methods need to be developed for automatically aggregating and, more important, for evaluating and distributing locally initiated optimizations and best practices.

(3) Which digital aides can help in accelerating decentralized implementation of change?

When changes in production structure are no longer an extraordinary event but turn into everyday business, this imposes an enormous burden on production workers. Apart from non-technical measures like qualification and training, it is of crucial importance to provide shop floor workers with adequate tools and methods that enable them to cope with the changes. Technologies of the digital factory can help to reduce the complexity resulting from changes in production in three different ways.

First of all, tasks connected to change that today are carried out manually by the workers can be automated. Machines will need to be provided with the capability of describing and configuring themselves, such that changes can be conducted requiring minimum effort on the one hand and leading to an automatic, consistent documentation in terms of digital models of the overall production system on the other hand. An example to illustrate this can be a mobile production robot that is able to adapt its setting and its programs depending on the current cell configuration and layout and to communicate these changes back to central planning.

Second, technical equipment can provide the worker with active support in comprehending a new production setting. The key premise is an ambient and minimum-obtrusive support of the worker. Technologies like Augmented Reality offer a promising approach to realize information systems that guide workers through production processes in dynamic environments, as pick-to-light systems do in static ones today. Again, context-awareness and self-description will play an important issue when it comes to supporting shop-floor workers in complex and constantly varying tasks. Therefore, sensing technologies for identification (like RFID) and localization and self-description will have to be developed further.

Third, if a fully automated adaptation of a production system is not feasible, the complexity of a manual adjustment needs to be reduced as far as possible, e.g. by intuitive human-machine interfaces (HMI). Again, technologies like Augmented and Virtual Reality can be used to create HMIs that allow for a fast and efficient configuration and programming of automated production systems without requiring expert knowledge. Production workers should be empowered by digital aides to accomplish as much change as possible by their own without requiring long iteration cycles and the involvement of experts from central planning units.

6 SUMMARY

This paper gives an analysis of the potential that is inherent in a successful integration of the paradigm of changeability on the one hand and the methods and tools of the digital factory on the other hand. It is shown, that the digital factory today in both its conceptual design and its implementation supports changeability but only to a limited degree. The authors come to the conclusion that the combination of the two concepts provides an immense potential which is not yet being used to the full extent. Future research directions are analyzed and it is shown, that a symbiosis of the changeable and virtual production is not a mere aggregation of two known concepts - the emperors new clothes - but indeed a key factor for companies' future success.

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8 BIOGRAPHY

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