TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special I, February, 2024

THE IMPACT AND CHALLENGES OF INDUSTRY 4.0 ON FACTORY DESIGN, ORGANIZATION AND MANAGEMENT

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Abstract: *The fourth industrial revolution is on its way to reshape manufacturing and value creation in a profound way. The underlying technologies like cyber-physical systems (CPS), big data, collaborative robotics, additive manufacturing or artificial intelligence offer huge potentials for the optimization and evolution of production systems. However, many manufacturing companies struggle to implement these technologies. This can only in part be attributed to the lack of skilled personal within these companies or a missing digitalization strategy. Rather, there is a fundamental incompatibility between the way current production systems and companies (Industry 3.0) are structured across multiple dimensions compared to what is necessary for industry 4.0. This is especially true in manufacturing systems and their transition towards flexible, decentralized and autonomous value creation networks. This paper shows across various dimensions these incompatibilities within manufacturing systems, explores their reasons and discusses a different approach to create a foundation for Industry 4.0 in manufacturing companies.*

Key words: *Industry 4.0, Factory Planning, Technology Planning, Operational Control, Tool Making, Manufacturing Process Chains*

1. INTRODUCTION

Manufacturing companies in almost all industries are facing multiple challenges, both from customers and markets as well as from advancing manufacturing and information technologies and shifting manufacturing paradigms. [1–4]

Where in the past market developments, production volumes and customer needs were relatively stable and limited, the globalization and regionalization of markets and the customers demand for increasing individualization options have shaken and shattered the stability and predictability contained therein [5–8]. These changes in the environment dramatically impact the target hierarchy for production systems in terms of what is the most important aspect of the factory within the design process (e.g. costs per unit manufactured, economies of scale, versatility, robustness, flexibility) [2,5,9,10]. Flexibility and changeability of the production systems is becoming more and more important, due to these market-side developments.

The same pressure towards change can be observed when looking at the technological side, encompassing both manufacturing technologies as well as the entire IT-infrastructure applied within the manufacturing sector. The fourth industrial revolution and the digitalization of the industrial manufacturing is gaining more and more momentum [4,11–14]. Technologies like artificial intelligence (AI), Additive Manufacturing, collaborative robotics, cyber-physical systems (CPS) and cloud computing are getting more and more advanced, affordable and easy to use, offering companies entirely new ways to communicate, manage and organize their production systems. [10,11,15,16]. Carefully and consistently integrated into existing production systems and factories, they hold the potential to counter some of the challenges inflicted by the changing markets and volatile customers [16,17].

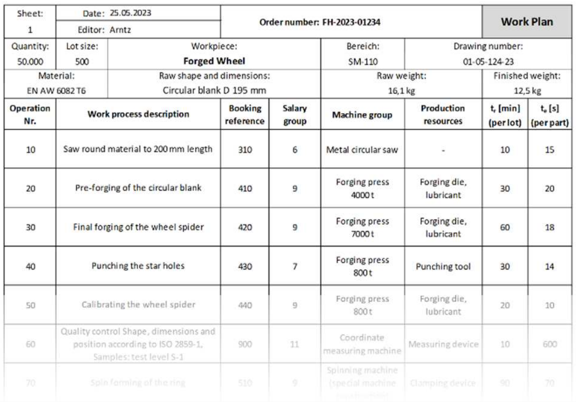
However, in order to harvest these benefits and unearth the potential, the fundamental logic of how production systems are structured and operate must be challenged and also the way these systems are designed and configured [1,2,5,18].

2. PROPBLEM DEFINITION

Two of the biggest challenges for manufacturing companies in order to fully adopt industry 4.0 technologies and use them to counter the shifting market demands with more flexible, changeable and adaptive production systems, lie in the way factories are usually designed and the IT-systems, that are used to manage and operate these systems.

2.1 The problem with current IT-Systems and the general data structure

The IT-systems currently used to manage, steer and generally operate manufacturing systems have developed in parallel and synergistically with production systems since the 1970s [19–21]. The foundations in terms of how the manufacturing related data is structured, how production programs and manufacturing processes are planned and quantified strategically, tactically and operationally linked to production resources and manufacturing equipment is the same today as it was 50 years ago. The means of choice is the work plan or process plan. The process plan connects products to machines and equipment and specifies the sequence, in which the necessary processes need to be performed in order to generate a desired outcome [22–24]. An exemplary work plan in displayed in figure 1.



Sheet: 1
Date: 25.05.2023
Editor: Arntz
Order number: FH-2023-01234
Work Plan
Quantity: 50.000
Lot size: 500
Workpiece: **Forged Wheel**
Bereich: SM-110
Drawing number: 01-05-124-23
Material: EN AW 6082 T6
Raw shape and dimensions: Circular blank D 195 mm
Raw weight: 16,1 kg
Finished weight: 12,5 kg

Operation Nr.	Work process description	Booking reference	Salary group	Machine group	Production resources	t_r [min] (per lot)	t_e [s] (per part)
10	Saw round material to 200 mm length	310	6	Metal circular saw	-	10	15
20	Pre-forging of the circular blank	410	9	Forging press 4000 t	Forging die, lubricant	30	20
30	Final forging of the wheel spider	420	9	Forging press 7000 t	Forging die, lubricant	60	18
40	Punching the star holes	430	7	Forging press 800 t	Punching tool	30	14
50	Calibrating the wheel spider	440	9	Forging press 800 t	Forging die, lubricant	20	10
60	Quality control Shape, dimensions and position according to ISO 2859-1, Samples: test level S-1	900	11	Coordinate measuring machine	Measuring device	10	600
70	Spin forming of the ring	510	9	Spinning machine (special machine	Clamping device	90	70

Fig. 1: Exemplary work plan

In the environment of the late 1070s and 1980s, this direct linkage between products and manufacturing resources wasn`t problematic, due to the very limited width of the production programs (e.g. in car manufacturing). However, against the backdrop of the initially presented global developments and shifting markets, this form of allocation between products and resources is severely outdated, since it causes rigidity and inflexibility as well as unnecessary complexity within the manufacturing systems. Furthermore, it prevents manufacturing companies to manage and steer their production system more flexible and dynamic and prevent planners from designing more flexible factories in the first place (c.f. chapter 2.2).

Most IT-systems used for the management, steering and development for manufacturing companies, are still based on the work plan as the core element to connect products to machines. At all stages of the automation pyramid (see figure 2) work plans are used to schedule products and manufacturing lots and to allocate resources. In the industry 3.0 world of most manufacturing companies, this causes complexity, longer lead times, inefficient resource allocations and severely limits the flexibility of the production systems.

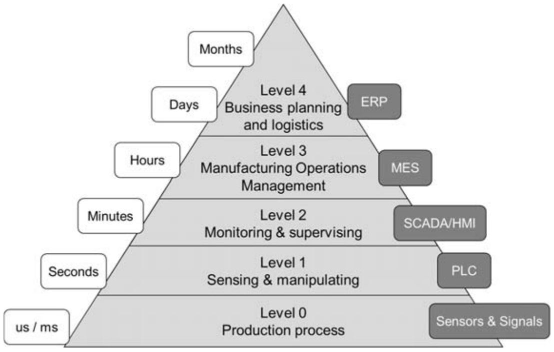


Fig. 2: The automation pyramid according to the ISA 95 model [21]

Furthermore, this kind of information architecture is incompatible with the kind of autonomous and self-controlling production systems envisioned in the industry 4.0 era, that will help to tackle the arising challenge mentioned in the introduction. Where in the industry 3.0 automation pyramid products and resources are allocated and matched via the work plan, they will be dynamically and situationally allocated in the industry 4.0 production systems. The fundamental logic of such a system is displayed in the following figure 3.

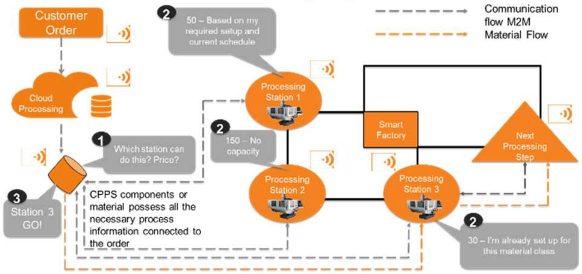


Fig. 3: Schematic representation of an agent-based SOA planning and control logic (derived from [25])

In order to facilitate this dynamic and situational allocation of resources and processes as it is envisioned and often described in the context of Industry 4.0 (for example in the context of service oriented architectures in manufacturing systems or agent based production scheduling), it is necessary to establish an information basis, that is not limited by the direct and rigid linkage of production resources and products but rather flexible and adjustable and easily expandable and modifiable. The same is true for the general physical structure and design of the industry 3.0 factories and the way these systems are designed (c.f. chapter 2.2).

2.2 The problem of defining technologies and boundary conditions too early

When looking at the classical procedure of planning tasks for industrial production sites, a strictly sequential process can be observed.

Starting with a strategic technology-planning phase, long time assumptions are regarded to understand overall changes in markets, products and manufacturing technologies that evolve and gain new abilities in achieving quality requirements and reducing production costs. The main target of such considerations is to prepare production companies for long time changes and possibly disrupting developments, which could endanger today's way of production and the associated business models. In this phase, long-term decisions are prepared in order to know the market, product and technology environment well [42,45]. As soon as a concrete investment decision is due, operational planning can be started much faster in this way.

During the operational technology-planning phase, the product spectrum to be produced is being analyzed and technological options are derived which are capable to process the required materials and geometries and to achieve the foreseen quality requirements [34,38,39]. The major result of this technology planning phase are process chain alternatives, which can be assessed according to variable targets, such as process time, logistics effort, process cost or environmental impact [42, 43]. Based on the overall strategic targets of the respective company, a decision has to be made to favor a certain process chain. This decision typically encompasses the technologies itself, such as a deep drawing process, cold forging or five axis milling process e.g. Implicit in this decision, however, are far more determinations.

When analyzing this sequential approach, it is noticeable that it inevitably leads to an early and rigid specification of a large number of determinants. In the technology-planning phase, for example, it is possible to develop, compare and evaluate different variants of process chains. However, the interfaces between the individual phases, and here in particular the transition between the technology and factory planning levels, are designed in such a way that in each case only finished options are handed over which make very concrete determinations. This classic approach thus in no way fulfills the above-described need to respond with high flexibility to the greatly increased variability of requirements and boundary conditions in industrial production [41].

In order to design and plan the hybrid and more flexible factories and production systems of the future, it is necessary to keep the flexibility available in the early stages of the technology-planning phase available for further planning steps. A different logic for the description of the necessary transformations within production systems at various stages and with varying degrees of granularity is needed.

3. A TASK BASED DESCRIPTION MODEL FOR MANUFACTURING SYSTEMS

In order to solve the fundamental problems described above, it is necessary to structure and allocate information within manufacturing companies differently. The rigid link between processes and machines and thus the inflexibility when it comes to dynamic resource allocation and continuous production system optimization, needs to be broken up and replaced by a more flexible logic [5,10]. The basic task logic described in the following paragraph has proven to be an efficient concept and informational basis for the fourth industrial revolution in manufacturing. The description of the basic task logic is deliberately short. For a more extensive presentation and discussion within different fields of application (e.g. additive manufacturing, flexibility or logistics planning), the following references are suggested [5,10,26–28].

The core of the basic task logic is the separation or decoupling of the content of the process (what we call the transformation) and the machine that is actually performing this transformation. Every product has a distinct number of transformations that need to take place in a specific order to achieve the desired outcome (the sellable product). Each transformation can be identifiable by the necessary transformation, the input and the generated output. Such a unique combination of input, output and transformation is called a basic task. A chain of basic tasks is the abstract representation of the necessary transformation that constitutes the manufacturing process of a product. The assignment of a task to a specific machine does create the actual manufacturing process or basic process. So for each task, depending on the necessary transformation and the properties if the item involved (input) there is a number of machines within the production system, that can perform the necessary transformation and this has the "skill" or "competency" to perform the basic task. The following figure 4 exemplifies this.

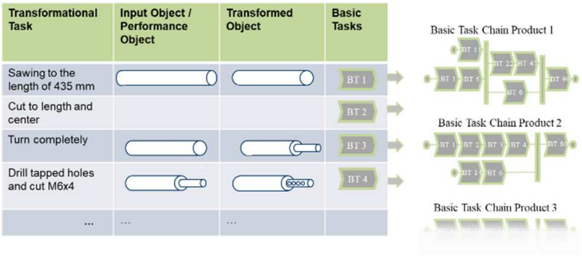


Fig. 4: Fundamental logic of basic tasks (based on [5])

In decupling the what (necessary transformation) and the how (machine), the basic task logic offers a solution for the fundamental problem the work plans from the industry 3.0 logic pose for the development of a more flexible, autonomous and decentralized production systems. The fundamental operational potential regarding agent based autonomous operational control in the context of service-oriented architectures in manufacturing have been discussed by Luft et.al. The following chapter is therefore dedicated to the potential impact a more flexible, task oriented allocation logic can have on the design of the factories as a whole.

4. APPLICATION FIELD FACTORY PLANNING

The authors have shown, that in the area of factory and technology planning, the basic task logic facilitates a paradigm shift when it comes to the design of industry 4.0 factories. Due to its self-similarity and transformation focused nature, it bridges the currently existing gap between different stages of the factory planning and design process. Furthermore, it is compatible with the process oriented factory planning approach developed by KUHN et.al., which is based on the value chain model of PORTER and the logistical value chain model by KLÖPPER [29–32].

Using the basic task, necessary transformational tasks within the manufacturing process of various products can be described in a reasonably abstract way, that both grants additional degrees of freedom in later planning stages but simultaneously allows for a sufficient level of detail regarding technological considerations. This is an important novelty of this approach: it is self-adapting regarding the level of detail required in different stages of the production and factory planning processes.

The tasks connect product related requirements at different stages with the capabilities of different manufacturing technologies. Comparing the resulting transformational task chains across various iterations generates a solution space in which various technologies can be used to realize specific component requirements.

In a consecutive step different technologies out of this solution space must be combined into process chains. In this context, it is necessary to distinguish between technologies that produce the basic geometry of the desired object and the technologies that further modify and finalize the properties.

To illustrate this approach, consider an example from industrial production. Tool making is characterized by the fact that highly complex, difficult-to-machine products are manufactured. These are often manufactured as one-offs, but in any case, with low quantities and a very large number of variants. In addition, the manufacturing process chains consist of a large number of individual technologies, in which 20 or more steps often have to be taken into account. Classical technology and factory planning approaches quickly reach their limits in this environment, because the route to the production of a component or a specific geometry feature is not unique. Rather, there are typically different technology sequences that result in a qualitatively flawless component.

An obvious example is the production of a cavity in hardened tool steel. It can be machined by a sequence of soft milling, hardening, hard milling and grinding. Equally, however, a route via hard milling and grinding is conceivable - or the route via hard milling and electrical discharge machining (EDM). Such alternatives often concern the central steps of a machining route, but they can also concern upstream steps or surface treatments as the final manufacturing steps. Which of these routes is optimal in each case in terms of time, costs, sustainability or other target variables depends on a large number of influencing variables, which in many cases can even change on a daily or hourly basis. This is where flexible planning approaches show their great strength, as they favor fast reactions and thus a more economical production overall.

In our example, the basic task to be realized would be characterized by “material removal, material hardness 55 HRC, maximum depth 100 mm, minimum inner vertical radius 6 mm, minimum inner horizontal radius 2 mm, etc.”.

Several technologies are now capable of performing this operation. This results from a comparison of the defined requirements with the attribute set of each of the technologies. In our example, these are soft milling, hard milling and EDM. However, they differ in terms of performance as well as the required input variables and the feasible output variables. This is then taken into account in the next step when combining them into possible process chains.

The technologies marked in such a way are linked to process chain alternatives, which all are representatives of the same underlying transformational basic task chain. Although this necessarily restricts the solution space, it does so far less than in the classical approach described above (c.f. chapter 2.2).

Unlike classical approaches, the process chain variants developed this way can now be evaluated in part or as a whole and serve as a basis for the further planning steps in the overall factory planning process. In contrast to the classic factory design approach, the evaluation of the general factory design is not based on a fixed process chain, but on a bundle of alternatives. These are described in such a parameterized way that target values for planning can be flexibly adapted to current changes. This makes it possible, taking into account the boundary conditions for investments, etc., to define these technology chains as late as possible in the factory planning process - and thus to achieve a much better balance between flexibility, costs, lead times and system robustness in the overall systems design. This is a considerable and important advantage of the new solution developed by the authors: The planning flexibility is maintained at a high level as long as possible. Restrictions are only introduced, when necessary, and alternative process chains are kept within the solution space. Thus, in any case of changing boundary conditions, those alternatives are directly available for the further planning steps. This makes planning faster, more flexible and faster.

5. CONCLUSION AND NECESSARY FURTHER RESEARCH

Manufacturing companies are facing new challenges both on the market and technology front. Unpredictable markets in terms of demand and development require more flexible, robust and adaptable production systems. And even though the technologies propelling the fourth industrial revolution offer some potential solutions for these challenges, the successful implementation will require a fundamentally different way of allocating information at the core of manufacturing and also a different way to design manufacturing systems. The logic displayed in this paper offers a solution for this problem, since it enables companies to design more flexible systems by allowing a more flexible and holistic way of factory planning with a better integrability of planning results on different stages into the overall planning process. Especially when looking from a technological perspective, this approach drastically increases the flexibility to make late decisions. This is a considerable advantage, as it enables a flexible reaction to changes in the production environment.

The essential novelty of the developed approach is that alternatives and opportunities are preserved as long as possible during the planning phase. With the task-based description model, activities and transformations are abstracted and assigned to concrete technologies only as late as possible. This increases the flexibility of solution finding and is a key competitive advantage in the context of today's challenges in industry.

However, even though this logic has proven effective and applicable in different areas like factory flexibility assessment and quantification, there is still a lot missing to make it work across all phases of the factory lifecycle.

Apart from software systems capable of integrating the information needed, gathering the required information regarding the actual capabilities of manufacturing technologies will be an important issue. Technologies evolve fast, so there is a need for actual databases incorporating the required information.

Furthermore, even though this logic has proven effective and applicable in different areas like factory flexibility assessment and quantification, there is still a lot missing to make it work across all phases of the factory lifecycle. Aspects like how precisely the information needs to be for certain planning iteration and phases needs to be defined. In the beginning stages of the planning process, a rough transformational chain is usually sufficient, whereas in the later stages of the process more details need to be incorporated and thus, integrated into the task logic.

The same is valid for aspects like energy consumption, working conditions as well as connectivity, communication and information flow and sharing along the value creation chain of the different products. The same needs to be taken into consideration when looking at the different stages of the factory lifecycle and its different stages and configurations.

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IMPACTUL ȘI PROVOCĂRILE INDUSTRIEI 4.0 ASUPRA PROIECTĂRII, ORGANIZĂRII ȘI GESTIONĂRII FABRICILOR

Rezumat: Cea de-a patra revoluție industrială este pe cale să remodeleze producția și crearea de valoare într-un mod profund. Tehnologiile care stau la baza acestora, cum ar fi sistemele cibernetice-fizice (CPS), big data, robotica colaborativă, producția aditivă sau inteligența artificială, oferă potențiale uriașe pentru optimizarea și evoluția sistemelor de producție. Această lucrare oferă exemple pentru a crea o bază pentru industria 4.0 în companiile de producție.

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