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Agile Production Systems for Electric Mobility

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Abstract

Against the background of growing environmental awareness and ambitious international efforts against global warming, sales in the electric mobility sector are expected to rise steadily in the coming years. However, volatile markets accompanied by shorter product life cycles and uncertainties regarding legal, political and technological developments make it still difficult to forecast accurate figures and requirements of components such as batteries or electric motors. Therefore, the investment in highly productive but non-versatile production lines must be seen as a risk. Instead, the tension between need and uncertainty causes a need for rapidly adaptable, profitable production systems with low investment risk. In literature, the term "agile production systems" is often used in this context. Based on an extensive literature review, this paper therefore presents the state of research and attempts to develop a general definition of agile production systems in the context of electric mobility. In particular, relationships to existing production concepts are considered. The practical implementation of agile production systems is described using two different case studies. On the one hand, agile battery cell production based on modular and fully enclosed robotic cells is presented. This approach, based on microenvironments with adjustable humidity, enables a highly automated pouch cell production that is flexible in terms of material, number of units and format. Furthermore, the case study of an agile electric motor production is presented. Process chains of rotor and stator production are analyzed and an approach to conceptualize an agile production system for electric motors is introduced.

Keywords: Agile Production System; Electric Mobility; Electric Motor Production; Battery Cell Production

1. Motivation

The current trend towards shorter product life cycles and a growing number of variants, coupled with high technological uncertainties as a result of the transformation to electric mobility, presents the major challenges of automotive industry regarding production. This change is accompanied by increasing competition from up-and-coming pure electric car manufacturers, which comes along with cost pressure. In production, established transfer lines, which cannot be economically adapted on demand, are reaching their limits. Refinancing the production system within a single product life cycle is hardly possible anymore. These requirements result in the need for agile production systems that are flexible in terms of production capacity as well as product variants and that are characterized by an ability for rapid reconfiguration in both production equipment and control.

2. Agile Production Systems

Such production systems are still inadequately described in literature at the shop-floor-level regarding machinery. There, either highly productive, fast and specialized or highly flexible, slow and low capacity production systems are discussed. However, uncertainties of electric mobility call for quickly adaptable and scalable multi-machine

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systems in particular. At the production system level, such production systems are referred to as agile.

2.1. Research on existing definitions

Adaptive production is described by the term flexible production system. Sethi, A.K. and Sethi, S.P. give a general overview of flexible production systems and address the trade-off between flexibility, productivity, quality and automation level [1]. Gerwin considers them primarily from an economic management perspective [2]. Browne et al. specify flexible production systems on plant level by the eight flexibility types machine, process, product, routing, volume, expansion, operation and production flexibility. The focus of the technical explanations is on machine tools for metal cutting [3]. Due to their adaptability, flexible production systems present the basis for agile production systems. The concept of agile production systems extends the concept of flexible production systems by focusing on fast adaptability even to unexpected events.

The term agile comes from Latin term “agilis” and means “to drive, be in motion, do or perform” [4,5]. Consequently, agile production systems should be able to react quickly to changing market requirements [6]. This increases their own competitiveness and enables high profit margins, especially at the beginning of product life-cycles, due to high demand compared to supply (seller's market). Such effects were also evident at the beginning of the Corona pandemic, especially in Europe, when protective masks were traded at significantly higher prices than before. Hence, the domestic industry built up its own mask production, but by the time it started production the attainable market prices had already fallen. As a result, the contribution margins for financing the newly built production facilities had also fallen.

Agility as the key to rapid response to new challenges can be found in literature, particularly in the context of software development, product development and with regard to the organization of a company. In the field of production, Nagel and Roger were the first to deal with this topic in 1991 in the context of customer-internal production [7]. In 2012, Althaler et al. focused on economic production in a volatile environment [8]. In this context, Yusuf et al. in 1999 set their focus on rapid reaction to market demands [6]. Furthermore, Schuh et al. described Industry 4.0 as a central enabler for more agility in manufacturing companies in 2020 [9]. These authors reflect the scientific discourse, which is characterized by a high system level and from an organizational perspective. In contrast, the following chapters describe what agile systems in engineering can look like on shop-floor-level from the authors' perspective in order to make production more agile.

2.2. Differentiation of production systems

In this paper, production systems are divided into flexible production systems, agile production systems and transfer lines. According to Fig. 1, the authors of this paper classify

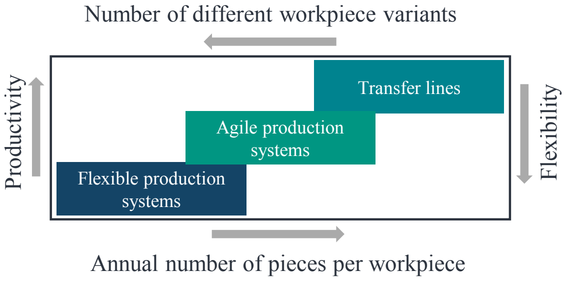

Fig. 1: Comparison of productivity and flexibility of production systems

agile production systems between highly productive transfer lines and flexible production systems with limited productivity in order to combine the positive characteristics of both approaches: high flexibility and productivity with short throughput times.

The advantages and disadvantages described before result from specific characteristics of the corresponding production systems – e.g. type of machinery, production layout, type of interlinking or material flow – as they are schematically shown in Fig. 2. The material flow leads along specific paths through various functional units according to the connections and arrows. A functional unit is defined as an independently functional part of the production equipment to perform a process step along the process chain consisting of one or several manufacturing or assembly operations. Dashed arrows represent alternative paths a product can take through the production system.

Transfer lines (see Fig. 2.a) such as those used for mass production in the automotive industry, are characterized by a fixed and non-versatile serial sequence of process steps – the so-called rigid chronological order [10]. The functional units are rigidly chained, directly linked to the production cycle-time and no buffers are required. If one machine fails, the entire transfer line comes to a standstill. To reduce the cycle-time, machinery and production equipment are optimized for individual products. Consequently, the production of different products is only possible to a very limited extent.

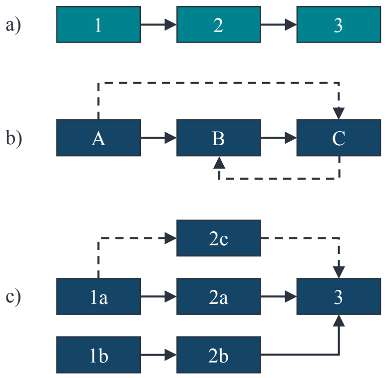

Fig. 2: Schematic structure of transfer lines (a), flexible production systems (b) and agile production systems (c). Rigid special machines are shown in turquoise, flexible single machines in blue. Dashed arrows show an alternative value stream and solid arrows show the regular value stream.

In contrast, the sequence of process steps in a flexible production system is freely configurable to a certain extent (see Fig. 2.b) and not synchronized to the cycle time. Such production systems are used, for example, to manufacture large aerospace components made of aluminum [10]. As a consequence, there is a need for large workpiece buffers, but also the possibility of bypassing individual machines in the event of damage to ensure a throttled but still continuing production. In addition, the use of flexible machines enables the parallel production of different products. Agile production systems take up characteristics of the other two systems and combine them (see Fig. 2.c). These production systems are used, for example, to manufacture internal combustion engines for premium passenger cars. The structure and mode of operation of agile productions systems are described in the following chapter.

2.3. Structure of agile production systems

Agile production systems are designed to combine the advantages of both transfer lines and flexible production systems. From the authors' point of view, this means that the production system can be quickly adapted to the product to be produced and the quantity demanded, while at the same time ensuring high plant utilization. Consequently, certain characteristics of both production systems must also be combined. The desired high productivity is achieved by the fixed sequence of processes corresponding to the material flow in a transfer line. This enables deterministic and thus simple production planning that is less prone to error, as required by agile production systems due to volatile boundary conditions.

Execution times of an agile production system will usually be higher than those of a transfer line, as its high productivity is difficult to achieve due to the lack of plant specialization. However, the setup times are considerably lower due to the agile concept, so that the order or occupancy time is shorter and products can be delivered earlier, especially in a production with many variants. Batch sizes depend on the product to be produced and the plant technology. To determine the optimum, a material flow simulation can be carried out, for example.

To accommodate the demand for flexibility in terms of throughput and product variants, both the production layout and the functional units of agile production systems must be flexible and modular in design. As described above, the term *functional unit* refers to an independent and fully functional subsystem of the agile production system that performs a process step along the process chain, such as the balancing rotors in electric motor production. One level lower in the system hierarchy, there are *machine modules*, which contain machinery including associated functional and safety controls. These in turn contain *process modules* for executing the process steps, such as a drilling unit or a handling robot. At the lowest level of hierarchy there are modular tool or handling kits, which e.g. contain drills using the example of a balancing unit for electric motor production. This structure is shown in Fig. 3.

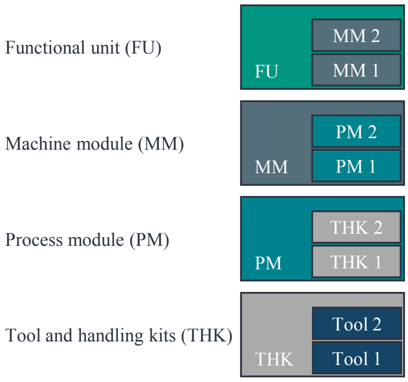

Fig. 3: Structure of functional units, machine modules, process modules and tool and handling kits.

By adding or removing functional units, the throughput of the production system can be scaled according to market demand while maintaining high plant utilization. The throughput of the individual functional units can vary greatly, as the practical example of battery cell production shows. In the agile battery and electric motor production described in more detail later, the material flow simulation software Tecnomatix Plant Simulation is used to find an appropriate configuration of the production system.

Agile production systems unfold their potential when the functional units and their interfaces are standardized, so that they can be exchanged across production systems and reused as needed. In addition, flexibility can be realized through the internal structure of the functional units. Three approaches for enhanced flexibility need to be differentiated within this context: structure-, kinematic- and tool-based flexibility.

- Structure-based flexibility:
  Standardized and modular structures of the functional units and the corresponding (sub)modules enable a quick adaption according to new requirements. For example, the functional scope of a functional unit can be expanded – or its degree of automation increased – by adding further process modules.
- Kinematic-based flexibility:
  Kinematic-based approaches offer the possibility of manufacturing different product variants with one single machine. Tool changes are replaced by a software-defined parameterization of the kinematics and set-up times can be reduced by digital twins.
- Tool-based flexibility:
  Also based on the modular functional structure of production kits, tool-based approaches can be applied to increase the number of product variants, which can be economically manufactured by the production system.

The selection or rather the amount of combination of the approaches introduced must be defined after a detailed analysis of the process chain for each production system. In addition, the product which needs to be produced, the number of variants and the expected fluctuations in the number of units, company-wide strategies and product portfolios must also be considered in order to be able to benefit from economies of scale beyond the boundaries of one single production system in the best possible way.

3. Case Studies

As pointed out before, the practical implementation of an agile production system at machine level directly depends on the products to be manufactured. In the following, approaches for agile battery cell production and agile electric motor production being developed at Karlsruhe Institute of Technology will be discussed in detail. Both concepts pursue the practical implementation of agile production systems in order to demonstrate the feasibility of flexible and fast production of these components, which are essential for electric mobility.

3.1. Agile Battery Cell Production

A special feature of battery cell production is the processing of moisture-sensitive materials such as lithium nickel manganese cobalt oxides (NMC) 811 for cathodes or the electrolyte. As a consequence, production takes place in drying rooms, which can normally be operated on a dew point temperature of about -50°C. In conventional production plants, which are usually specialized on a single type of battery cell with large special machines corresponding to a fixed production capacity, these drying rooms are relatively large. Moreover, they often contain multiple process steps with different requirements for the dryness of the air, whereby it may always be drier than required. For quality assurance reasons, however, the complete room must be designed and dehumidified with regard to the most moisture-sensitive process, which has a negative impact on acquisition and operating costs [11]. In addition, negative impacts on the environment must also be taken into account.

Agile battery cell production takes place in small local drying rooms. Hence, the dew point temperature of which can be individually adjusted. These rooms, also called microenvironments, are sealed off from the environment and, with their internal machinery, represent functional units in the sense of the introduced nomenclature. The prototype of agile battery cell production being developed at Karlsruhe Institute of Technology and outlined in Fig. 4 provides functional units for the process steps wet coating and drying of the electrodes, dry coating as an alternative coating process, calendering, separation and assembly. Each microenvironment contains a 6-axis industrial robot of type KUKA KR22 R1610-2 as handling module to automate the material flow. In combination with highly automated process modules, this ensures that no people are present in the microenvironments during production. This reduces employee exposure to hazardous substances and very dry air. There is no need for humans in the microenvironment, so less energy is needed to dehumidify the air. The material flow is realized automatically via material locks, whereby an infeed process takes approx. 2 minutes.

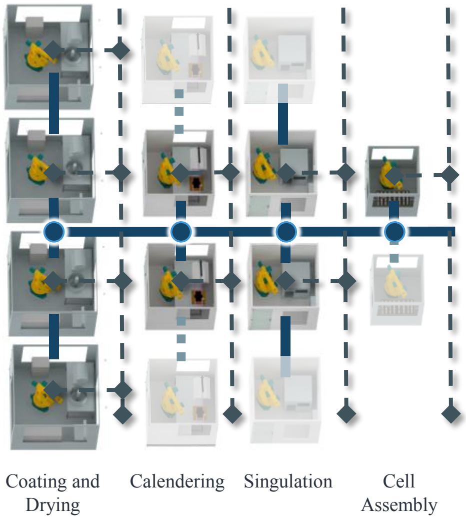

Fig. 4: Functional principle of agile battery cell production based on microenvironments equipped with machine modules. The capacity utilization can be kept high despite different processing times thanks to redundant functional units.

Instead of specialized machines, the functional units contain machine modules with a high flexibility corridor for the production of different variants. For the stacking process, such a machine module has already been developed as a prototype in a previous research project called SmartBatteryMaker (3-4332.62-KIT/9). It is capable of stacking both rectangular and trapezoidal electrodes without tool changes. This is made possible in particular by the adapted handling module. This process module gets its flexibility from the use of SCARA robots and a specially developed gripper at the level of the handling kits in the previously introduced nomenclature. Due to its curved shape, the gripper is able to accommodate different formats [12]. If this flexibility corridor should not be sufficient for an order, because larger cells need to be manufactured as an example, the modular design of the system allows the gripper to be changed quickly. This means that the flexibility corridor can be adapted quickly on the hardware side in the interests of adaptability [13].

The concept of agile battery cell production itself not only provides for the quick change of tool or handling kits, but also of process and machine modules up to the functional units. For this reason, the microenvironments will be designed to be transported via crane or forklift so that the production system can be adapted promptly as a consequence of changes in order situation. They will also have removable ceilings so that larger and heavier modules can be exchanged via crane. This allows an enhanced scalability of the agile production system by a gradual integration of process modules into the existing production system during start-up. In the event of fluctuations in sales or during the period of production phase-out, process modules, machine modules or functional units can be removed from the production system according to the same scheme and used to manufacture other products. Similarly, machine modules can be continuously developed further and adapted to new trends, so that the modular multi-machine system can always be kept at the cutting edge of technology.

To achieve maximum flexibility, the approach primarily provides for a sheet-by-sheet material flow. This is supplemented by a roll-to-roll material flow from conventional machines in order to examine the interfaces between agile battery cell production and conventional production in greater detail. In addition, the sheet-by-sheet material flow also simplifies the bundling and distribution of the value stream to redundant functional units in order to keep utilization high and throughput times low. To determine the optimum number of redundant machine modules, a plant simulation model is used. In the scope of this project, such effects are virtually investigated with the aid of a digital twin, whereby the real plant being built provides important input parameters.

3.2. Agile Electric Motor Production

The production of electric traction motors can be divided into three subsections: rotor production, stator production and final assembly. In the following, the processes for the production of permanent magnet synchronous machines (PMSM) with hairpin stators are considered and a systematic approach for the development of a production kit for agile electric motor production is presented.

3.2.1. Analysis of the process chain

As a first step, the fundamental process chain of electric motor production must be analyzed and system boundaries need to be defined. The result of this analysis is shown in simplified form in Fig. 5 using the example of a PMSM and stator manufacturing by hairpin technology starting with the incoming inspection of the rotor and stator stacks. The individual process steps represent the initial functional units of the production system.

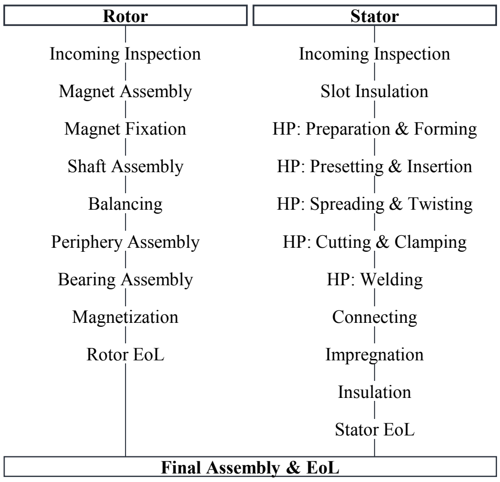

Fig. 5: Simplified process chain for rotor and stator manufacturing in the context of electric motor production (HP ≙ hairpin technology). Additional measuring and tempering processes are neglected to maintain clarity.

In addition, the individual processes can be analyzed in more detail. For this purpose, the standard VDI 2860, which provides symbols for the solution-neutral description of handling tasks, can be used for example [14]. The process times are then analyzed in order to be able to provide an initial estimation of the production capacity of each functional unit.

3.2.2. Analysis of process requirements

In order to be able to define requirements and specifications for the functional units, the requirements for each process must be analyzed first. These can be, for example, forces and torques, temperatures, temperature curves, traverse paths or tolerances to be observed. The results of these analyses are important for later standardization approaches of functional units as well as machine and process modules in particular.

3.2.3. Analysis of requirements for workpiece transport

The transport of workpieces also plays an essential role in the planning of agile production systems. For this purpose, a universal and standardized workpiece carrier is required, which can carry the occurring dimensions and weights of the workpieces – e.g. rotor/stator stacks, shafts or housings – with minimum set-up effort. For this purpose, the workpieces can be divided into geometry primitives such as cylinders, hollow cylinders or prisms first. Subsequently, these can be used to work out various operating principles for workpiece fixation as part of the concept development phase. In addition, it must be analyzed for which processes the workpiece can remain in the carrier, has to be lifted out or removed from the carrier.

3.2.4. Analysis of product-process-interactions

Besides the consideration of purely technical production aspects, product properties – e.g. weight and dimensions – and their effects on the production process must also be considered. For this purpose it is helpful to develop a product technology kit for electric motors, which can provide further indications of requirements for the production system. A future-robust design of this product technology kit enables the forward-looking planning of a production kit that can also meet future product developments. A model-based system engineering approach to help manage the complexity that comes along with modular product design is explored by Albers et al. [15].

3.2.5. Initial estimation of production capacity

With the help of evaluation tools based on Excel and VBA or more complex simulation software, initial estimations regarding the number of pieces that can be achieved with a specific layout of a production system can be made. Fig. 6 shows the implementation of an exemplary material flow simulation in Tecnomatix Plant Simulation, which can be used to initially estimate the production capacity of a production system with any number of functional units. These units can be activated (green dot) or deactivated (red dots) to generate the desired layout.

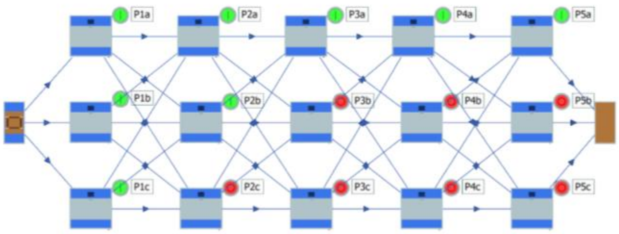

Fig. 6: Exemplary simulation model implemented in Tecnomatix Plant Simulation used for an initial estimation of the production capacity.

3.2.6. Summary

As the preceding analyses show, electric motor production is not a sequence of classic manufacturing processes based on CNC-machining. Hence, the process chain rather consists of special processes, such as magnetizing or impregnating, and assembly operations. In addition, the sequence of processes is fixed. Consequently, a flexible production system as presented in chapter 2.2 cannot be applied. Due to the uncertain framework conditions, the use of rigid transfer lines is also not economical in many future market scenarios. An agile production system, as presented in this paper, provides an acceptable compromise. With the help of the analyses presented, relevant requirements for the production system and the included functional units and modules can be defined and initial estimates can be made in order to lay the fundamentals for later practical elaboration.

4. Conclusion

In summary, the scientific discourse on the topic of agile production is mainly at a high system level. This publication shows what agile production can look like at the shop-floor-level consisting of machinery and other production equipment. The agile production system based on modular functional units is being established at Karlsruhe Institute of Technology in both the field of agile battery cell production and electric motor production. This enables ongoing scientific research into agile plant engineering in the growing but still volatile field of electric mobility.

5. Outlook

The goal of maximum standardization of the production system with the highest economic flexibility at the same time is being researched across applications at the KIT in the context of value stream kinematics [16]. This approach is based on both standardized kinematics, which are able to take over application-specific tasks by means of adapted end effectors, and an extensive digital process chain. Currently, this concept is applied in the field of disassembly and machining. The next step is to transfer this production principle to battery and electric motor production so that the special machines can be replaced by corresponding special end effectors.

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