Fluid Manufacturing Systems (FLMS)

A Novel Approach for Versatility in Production

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Abstract. Volatile market demands, stronger regionalization of markets, ever-shortening product and innovation cycles as well as an ongoing demand for individualized products increase the need for adaptable production systems. More than a century after the start of mass production, alternative production systems are required to go beyond the current state of the art concerning adaptability, flexibility and reconfigurability to market requirements and demands. Fluid Manufacturing Systems (FLMS) describe such new production system concepts. The basic idea is to dynamically adapt and change all logistics and production processes, based on the comprehensive application of cyber-physical production systems (CPPS), thus enabling ongoing change in setup, configuration and product scope. CPPS provide a high degree of changeability, thus allowing for fast adaptions of the system to the changing requirements. Therefore the processes are continuously assessed, benchmarked and reconfigured to match the functional capabilities of production and logistic resources to the actual requirements originating from products and external influencing factors. Within this paper, conventional production systems such as Dedicated Manufacturing Lines (DML), Matrix Manufacturing System (MMS) and Flexible Manufacturing Systems (FMS) are described and characterized using defined criteria. The paper closes with a description of the Fluid Manufacturing System (FLMS), the core hypotheses and the advantages of the presented concept compared to conventional productoion systems.

1 Introduction and Motivation

The growing world population, ageing workforce, ongoing urbanization and the need for sustainable economic actions are only a few challenges to be named affecting future manufacturing [1,2]. The continuous trend towards personalized

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products [3] leads to volatile and fluctuating market demands and reinforces the need for lower prices in shorter lead times in production engineering [4]. A fixed scope of production output and technological capability per production system does not seem to be adequate anymore. New technologies with disruptive character and the advancing speed of technological development further increase the need for adaptable and fast reconfigurable production systems allowing mass production for individualized products at a competitive price [1,3–6].

Manufacturing companies have to consider these challenges in order to meet the customer demands, choose the right production concept and maintain a competitive business [7]. High price pressure combined with high labor costs have forced manufacturing companies especially from high-wage countries to gradually globalize operations. The resulting globally connected manufacturing networks have had a positive impact regarding higher sales volumes, increased turnover and lower production costs. On the downside, the most recent economic world crisis, following the pandemic outbreak, brings to bear the downsides of globally connected manufacturing networks, which were not able to respond in time to required changes in product portfolio and market demands.

Due to the systematic restrictions of conventional production systems, such as Dedicated Manufacturing Lines (DML) or Flexible Manufacturing Systems (FMS) with limited changeability and long transition times, alternative production systems receive increasing attention over the past years [3,8–11].

The functionality-based, system-driven [12] continuous reconfiguration of flexibly linked process modules used in Matrix Manufacturing Systems (MMS) [8] and Reconfigurable Manufacturing Systems (RMS) [3] enables current trends in personalized production. Simulations showed that MMS can help to improve production performance when the product variance is high and the production volumes per product are low [9]. However, there is further potential for improvement especially in terms of delay of transformation and scope of adaptions to the production demands.

This paper outlines the concept of Fluid Manufacturing Systems (FLMS) combining the conceptual ideas of flexible linkage of production cells as well as continuous adaption and reconfiguration of process modules. FLMS further refines the granularity of process module design making use of the benefits in connectivity and data transparency provided by the comprehensive use of cyber-physical production systems (CPPS). In doing so, the production system is empowered to smoothly trace the required market demands and continuously adapts the system functional capabilities.

2 State of the Art

As stated in Sect. 1, companies face the need for changeable production systems. Different types of production systems have been developed over time with each system having its benefits and drawbacks. Table 1 evaluates (based on an expert survey) the introduced production systems regarding different criteria. The criteria are chosen to define a qualitative base to compare common production systems regarding their suitability for mass production of individualized products. This includes criteria indicating the ability to produce high quantities to competitive prices. Additional indicators such as the flexibility to variance-mix and the ability for reconfiguration are assessed considering the adaptability of the system design and the required efforts for adaptions.

Table 1. Comparison of DML, FMS, RMS and MMS

	DML	FMS	RMS	MMS
High capacity	●	◔	◕	◕
Permanent availability of full set of functionalities	◔	●	◑	◑
Ability to integrate multiple products and variants	○	●	◕	●
Flexibility to volatile market demand	◔	◑	◕	●
Flexibility to variance-mix	○	●	◕	◕
Integration of personalized products	○	●	◑	◕
Ability for reconfiguration	○	◔	◕	●
Integration of new technologies	◔	◑	●	●
Low operative complexity	●	◕	◑	◑
Granularity of adaption/reconfiguration	◔	◑	◕	◕
Low transition time for adaption	○	◑	◑	◕
Responsiveness to turbulence	○	◑	◑	◕
Low operation costs	●	○	◑	◑
Short lead times	●	◕	◕	◑
Suitability to produce in lot-size one	◔	◕	◑	◕

Legend: ●: well suited, ◕: mainly suited, ◑: partly suited, ◔: fractionally suited, ○: not suited

Dedicated Manufacturing Lines (DML)

Dedicated manufacturing lines are designed to produce one product at a defined volume. The system is characterized by the sequential organization of dedicated process modules and machines in one, unidirectional flow [13]. Through focusing on one product and only few product variants, the investment into hardware is low. The uniform product flow provides high productivity. This allows low operation costs, short lead times and minimal efforts for production control. On the other side, DML are limited in terms of flexibility. Therefore, fluctuations to product variety or production volume lead to system inefficiencies.

Flexible Manufacturing Systems (FMS)

To overcome the restrictions of DML regarding the aspect of flexibility, the concept of FMS was developed. Its approach aims at providing a permanently linked production system with various flexible process modules, offering a high degree of functionality [3]. Accordingly, a FMS is suitable to a production program consisting of multiple product-variants at small quantities [14], as it can flexibly change-over its functionality to the required product variety. FMS fulfill the criteria of producing multiple product families and variants at a time. However, despite their flexibility, FMS can hardly be reconfigured. Therefore, it is impossible to integrate additional products requiring further functionalities, unknown at the time of system design. Additional drawbacks are high initial investments and a lower outputs which challenge economic operations [3,14].

Reconfigurable Manufacturing Systems (RMS)
RMS again, were designed to overcome the limitations of FMS. They aim to achieve fast system reconfiguration by low transformation efforts based on a modular and adaptable production setup. Through modular design in electronics and mechanics, separate parts of the system can be easily exchanged to encounter volume change or new product variants [14]. Thereby, the advantages of DML (e.g. high throughput) are combined with the flexibility of FMS [3]. Accordingly, the assessment of RMS characteristics in Table 1 show a high fulfillment of all criteria. RMS are particularly beneficial regarding the integration of new technologies as well as all criteria related to the scope of flexibility. However, RMS lack in responsiveness to turbulences and system adaption times. This makes it a potentially unsuitable system for high market volatilities.

Matrix Manufacturing Systems (MMS)
The MMS consists of flexibly linked, usually dedicated, process modules. Each process module offers predefined sets of technological functionalities necessary for production. MMS enable new features of production control as each product is capable of defining an individual production path by choosing its process modules, depending on the available process module functionalities, assembly priority graph and current state of production resources. Cycle times of the process modules are no longer uniform and functionalities can be reconfigured considering a mid-term perspective [6,8]. Due to its structure and the optional flexible linkage of process modules, MMS show the highest capability for reconfiguration (see Table 1). Furthermore, the system structure shows advantages considering the integration of multiple products and variants at the same time.

It can be concluded, that the MMS design already combines many advantages of DML, FMS and RMS. However, the approach still lacks in terms of operation costs and the granularity of adaption. At the same time, the requirements for high production capacity and short changeover times are not completely fulfilled. To combine an extra granularity of adaption and shorter changeover times (low latency) at high production capacity, a new approach is required. This approach is represented by the proposed Fluid Manufacturing System (FLMS).

3 Definition of Fluid Manufacturing Systems (FLMS)

FLMS are an evolution of the Matrix Manufacturing System (MMS). FLMS concepts bases on the principle of ad-hoc resource allocation and reconfiguration to individual process modules for optimal manufacturing performance results. Comprehensivly using the benefits of cyber-physical production systems (CPPS) and their capability to self-integrate and -parametrize, process modules can be easily aggregated from single resources to advanced manufacturing systems. To fully leverage the potential of FLMS, all process modules are intended to be modular and mobile. The requirements into mobility and modularity allow for on-demand adjustments of capabilities and functionalities as well as adaptable production layouts. Thus, the manufacturing system is capable to iteratively reconfigure in variable steps to the currently required product configuration. This reconfigurability requires complex production planning and control logic considering previously unknown degrees of freedom in production system design.

The specific degrees of freedom for a MMS, such as **Operation Sequence** (specifies the sequence of work operations) and the **Work Distribution** (assigns the process modules to the production order) need to be expanded. FLMS open up the **Work Content** (defines the competencies of a specific process module) and the **Layout Position** (defines the position of production equipment within the shop floor).

The described bifurcation in process planning, making use of the additional degrees of freedom, have to be controlled efficiently in order to fully exploit the potential of FLMS. Either the product can be further manufactured at the next available process module, being capable to perform the required tasks or at the next idle process module, which can be reconfigured to the desired functional range in a feasible amount of time. So far, available control procedures do not cover these extended degrees of freedom, which reinforces the need for new procedures to be developed [15].

To understand the functional capabilities of every mentioned production system, it is important to distinguish three major process module types, see Fig. 1.

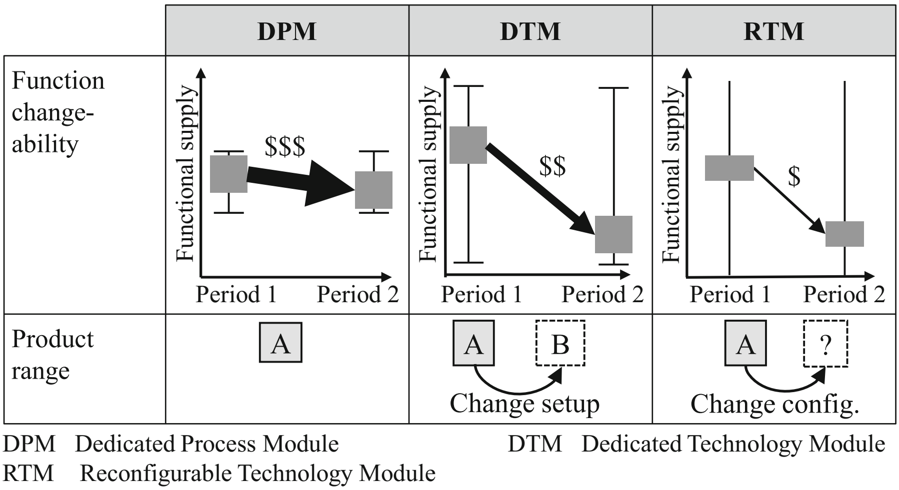

Fig. 1. Comparison of different process module types

- **Dedicated Process Modules (DPM)** are performing one single process task at a time. Functional changes are time-consuming and of high effort.
- **Dedicated Technology Modules (DTM)** represent the functional base of FMS. DTM are capable to deliver a wide range of built-in functionalities, meanwhile requiring high efforts in resources and time during design and implementation.
- **Reconfigurable Technology Modules (RTM)** are defined with narrow functional scope but wide modularity concerning electric and mechanical interfaces. The efforts for change are much lower due to the comprehensive use of CPPS (e.g. self-description of resources) in process module design and implementation.

Figure 2 depicts the concept and classification of FLMS in comparison to common production systems described in Sect. 2.

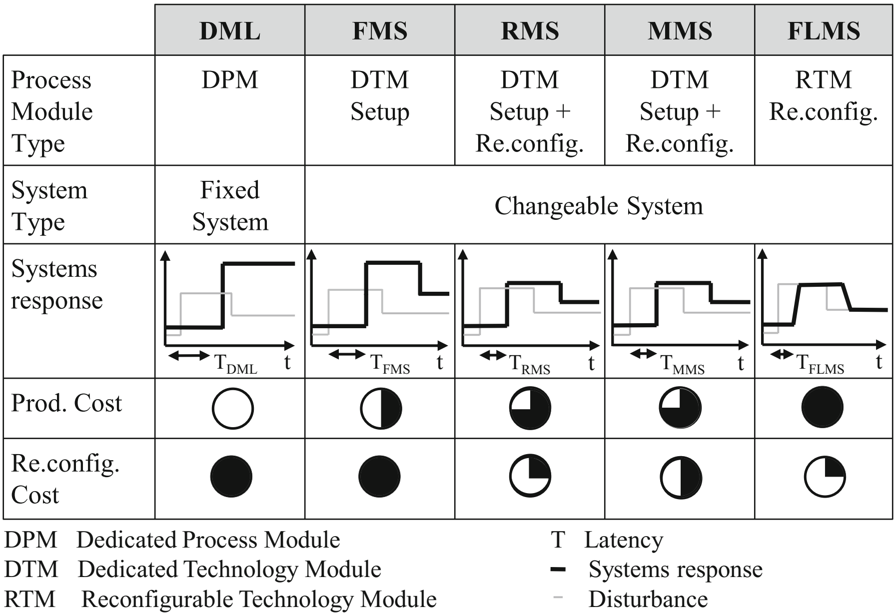

Fig. 2. Comparison of manufacturing systems

The system response of FLMS runs smoother and is not represented by box-shaped behavior, following the external triggers initiated by e.g. fluctuating demands or technical progress. Accordingly, the gap between functional requirements (gray line) and functional scope (black line) gets smaller and over-engineering in system design is avoided. According to Eq. (1), the system defined non-productive downtime due to adaption and reconfiguration (T_{FLMS}) for

FLMS is shorter than in any other production system. The non-productive downtime, a major cost driver in production systems, is considered to be the time between receiving a change order and the start of production.

$$T_{DML} > T_{FMS} > T_{RMS}, T_{MMS} > T_{FLMS} \tag{1}$$

The main reason lies within the FLMS architecture which fully consists of CPPS as the basic process module. This architecture implies the use of RTM instead of DPM or DTM and less engineering efforts during reconfiguration to guruantee a smooth approximation of the functional scope to external demands. A comparison of economic indicators reveals:

- DML and FMS are represented by low variable production costs, but higher costs during transformation.
- MMS, RMS and FLMS incorporate built-in flexibility due to versatile process modules for continuous integration and lower transformation costs.

4 Conclusion

The presented paper delivers fundamental definitions of the differences and limitations of common production systems used in today's manufacturing companies. In order to use the improvement potentials, highlighted in Sect. 2, the Fluid Manufacturing System (FLMS) is introduced and defined as a combined evolution of the MMS and RMS approach. FLMS are capable to ideally trace the systems' demand curve defined by production constraints and volatile market environments. Compared to other production systems, the system downtime caused by reconfiguration due to external trigger events is the lowest. Furthermore, the comprehensive use of CPPS in production system design might lead to better fitting functional scopes, the avoidance of over-engineering in system design, better adaptability to market demands, faster production ramp-ups and prevention of potential inefficiencies.

Further research shall investigate the production planning and control of FLMS, where additional degrees of freedom have to be controlled in order to fully exploit the potentials of FLMS. Furthermore, the implications of FLMS on the logistical processes and material supplies need to be considered.

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