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# Adaptation of Reconfigurable Manufacturing Systems for Industrial Assembly – Review of Flexibility Paradigms, Concepts, and Outlook

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**Abstract**

The introduction of new variants and continuously decreasing lot sizes following the paradigm of individualized production require the frequent reconfiguration of assembly systems. Albeit advances in ‘plug and produce’, current assembly systems remain limited when additional processes, changes in process sequence or processing time are required. This limitation is caused by physical constraints related to the typically employed fixed transfer systems (e.g. roll conveyors) and temporal constraints resulting from line balancing. Based on a review of the state of the art a framework is proposed to assess the adaptability of different flexibilisation approaches to industrial assembly. The matrix-shaped framework covers different levels of production systems from work stations to production networks on one axis and considers three different objects, i.e. technical resources, organization, and control and traceability on the second axis. Different criteria for assessment are assigned to each field of the matrix. Based on requirements derived from literature and discussions with experts from different industries it is concluded that the paradigm of Reconfigurable Manufacturing Systems (RMS) is suitable for adaption to small-lot and small to medium series assembly. Key boundary conditions for the application are outlined and further research topics to enable the application in industrial assembly are identified.

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*Keywords:* Reconfigurable Assembly Systems;Flexibility Paradigm; Changeability; Assembly System Design; Reconfigurable Manufacturing System

## 1. Introduction

Assembly is the final step in the manufacturing of complex products, using up to 50% of production time and accounting for up to 20% of overall cost and 20-70% of labor cost associated with production [1–3]. Assembly and assembly system design for typical manufactured goods (e.g. consumer goods, electronics, automotive industry), in this context referred to as industrial assembly, are driven by an increased number of product varieties resulting in increased complexity of both product and assembly processes while competition in global production networks increases simultaneously [4,5]. This leads to an increase in the rate of reconfigurations.

Currently deployed manufacturing systems are largely designed for stable market environments with less frequent changes in design and demand. Assembly lines are particularly sensitive to changes in process time, process sequence, or to the addition of new or changed processes. They are limited by physical constraints related to the typically used fixed transfer systems (e.g. roll conveyors) and temporal constraints resulting from line balancing and the elimination of buffers. This prompts the need for new approaches in assembly system design to allow manufacturing system changes [6,7].

The term changeability comprises means such as adaptability, modifiability, scalability, flexibility, and reconfigurability that are considered enablers for product variety management [5,8,9]. Flexible and reconfigurable manufacturing paradigms have been a subject of research for some time. Newer paradigms address scalability [10–14] with a focus on machining systems. Several approaches for assembly system design based on modularization emerged in


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recent years and were brought to the market as enablers (e.g. [15,16]) and are further brought on by recent developments in fields such as information and communication technology (ICT), joining, handling and process technology, digitalization, and virtualization [17]. However, while Reconfigurable Assembly Systems (RAS) have been the subject of extensive research including advances in mixed model assembly lines, modularization, and plug and produce, they remain limited by physical and temporal restrictions resulting from their configuration.

This paper aims to answer the question whether or not flexibilisation paradigms based on from other sectors of production can be adapted for the use in industrial assembly and if so under what conditions. Based on a review of the state of the art on flexible and reconfigurable manufacturing systems, requirements of machining and assembly systems regarding manufacturing system design are summarized. A framework for the review of flexibility paradigms is introduced and different evaluation criteria for comparison and assessment of paradigms are laid out. Criteria have been derived from literature, expert interviews, and the authors' own experiences. Conclusions regarding the adaptability of flexibility paradigms to industrial assembly are presented and further research tasks are identified. Examples are referenced to an abstract use case from engine assembly and related cylinder head machining.

In the following, the term 'manufacturing system' is used to refer to any system related to production consisting of work stations that are linked to some extent by a transfer system. These manufacturing systems perform either machining or assembly tasks and are referred to as assembly or machining systems respectively. While hybrid systems are generally known, they will not be considered in this paper for the purpose of conclusiveness.

## 2. State of the Art – Flexible and Reconfigurable Manufacturing Systems

The most effective way to achieve flexible manufacturing systems is during product variety management [5]. As this is not always possible, manufacturing systems need to be able to be reconfigured regarding two aspects. One is their functionality to produce different products, the other is their production capacity [12]. On the work station level this is achieved through universality and inherent flexibility (e.g. CNC machining center with tool magazine) or design for reconfigurability by defining product family related design and solution spaces (see [18,16]). On the line or segment level flexibility is largely influenced by the manufacturing systems' configuration.

Conventional manufacturing systems, with a strong focus on machining, rely on either dedicated manufacturing lines (DMLs) designed to produce mass production parts at the highest efficiency using purpose build machines. Another approach are Flexible Manufacturing Systems (FMS) [19–21] that typically use general purpose CNC machines to produce a number of different parts that previously known at reduced efficiency. DML become inefficient when product variants are required but provide high throughput, whereas FFS can be used to produce a selection of products but cannot be scaled in their output without large investments in parallel FMS [22,12].

*Koren and Shpitalni* (2010) therefore have introduced Reconfigurable Manufacturing Systems (RMS) as a solution that combines both DMLs' throughput and FMS' flexibility. Accordingly, a manufacturing system is reconfigurable when it is designed so that its physical structure can be changed easily and when it was designed for a part family instead of a product (e.g. a cylinder heads of car engines)[12]. DML, FFS, and RMS share their general components consisting of multiple manufacturing machines and a common transfer system. Suitable buffers and parallelization of machines allow the decoupling of the system's cycle time and cycle time for each individual work station [12]. Research on RMS has covered balancing (e.g. [23–25]) and possible configurations and their impact on productivity (e.g. [12,26–28]) largely with regard to machining.

RMS, as all manufacturing systems for industrial products, typically consist of multiple stages that partially process the product until it is finished. The configuration of a system decides over its productivity, responsiveness, convertibility, and scalability [12]. *Koren and Shpitalni* (2010) provide a method to classify the resulting configurations for multi stage systems. They differentiate between symmetric configurations (Fig. 1 a), c-d)) and asymmetric configurations (Fig.1 b)). Differentiation also results from the presence of crossovers (see Fig. 1 c) no crossover d) with crossover). Fig. 1 e) gives an example for a practicable RMS [12]. Scalability for RMS is achieved by adding more machines to a cell gantry (stripped box in Fig. 1 e)) providing more capacity for the task assigned to that particular branch. The route for each job is individually defined according to the availability of a machine and the job requirements (i.e. cylinder head #4578 route 1a-2b-3a; #4789 route 1b-2a-3b). The resulting scheduling is the biggest challenge when implementing such systems.

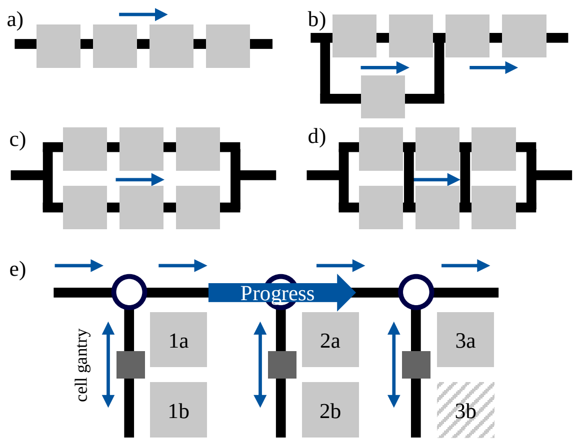


Fig. 1. Overview of selected RMS configurations (see [12]).

Even though the solutions introduced above are largely motivated from machining systems, they are generally applicable to assembly systems as well (furtheron referred to as Flexible Assembly Systems (FAS)). Research on achieving reconfigurability for assembly systems has largely focused on the work station and cell level. Research on interoperability with ease of control system reconfiguration in mind has been carried out under the term 'plug and produce' (e.g. [29–32], further work within the Industrie 4.0 scheme in Germany and the Internet of Things (IoT)/ Industrial Internet Consortium (IIC)). [33,17,34,35] give a brief overview on recent approaches in the research of RAS. At the time of writing applications of and research on using RMS style configurations for industrial assembly systems is not known.

## 3. Requirements of Machining and Assembly Regarding Manufacturing System Design

The requirements of assembly and machining systems towards the design of manufacturing systems have common and differentiating characteristics which require careful evaluation in order to be able to assess the adaptability of approaches from the respective other domain.

Assembly and machining share requirements regarding the provision of information and energy but differ in material flow. While machining operations primarily require rough parts, tools, and auxiliary material (e.g. coolant, cutting fluid) and transform these into finished parts, chips, tools, and remaining auxiliary materials, assembly operations involve a more complex material flow. As assembly operations by definition require the presence of two or more specific parts or subassemblies to form (another) subassembly or product, the material flow involves several parts in addition to auxiliary materials (e.g. welding gas, glue). In most assembly operations the parts that are assembled to the main product represent significant monetary values and are often responsible in defining product variants. In the interest of efficient assembly systems these parts are provided to the assembly process just in time (JIT) and just in sequence (JIS) and cannot be stored at the assembly station in advance.

The fundamentally different operations in assembly (e.g. screwing, welding, pressing) and machining (e.g. grinding, milling, turning) result in different requirements towards the deployed machines. Machining systems usually rely on machine tools based on rigid and heavy machine beds with several computer controlled axis to execute NC programs. Their range of tasks is limited only by the working volume and achievable accuracy. Fixtures and available tools are typically designed to be highly universal and standardized and do not present inhibitors for changeability. The resulting universal machines have a high inherent flexibility [36,11]. Assembly work stations in general are limited by the extent to which fixtures can be used for different products and the amount of different parts that be provided given space constraints. Automated assembly work stations are largely single purpose machines specifically designed for a single task. Changes in process direction (e.g. the direction a screw is driven) often result in a major redesign of the mechanical structure of the work station. Work stations based on industrial robots have a higher flexibility, but are limited by the adjustability and exchangeability of fixtures used to position parts (see [36] for an analysis of change inhibitors in assembly systems). Manual assembly work stations have the highest degree of inherent flexibility and can be reconfigured with the least expense besides fixtures. Compared to NC-machines assembly stations cannot be considered universal, resulting in a limitation of how many different assembly operations can be executed within one (automated) work station.

Regarding organizational aspects, both domains differ in the rigidity of process sequences. While machining tasks often have a very linear process sequence that does not allows for variations in process sequence, assembly tasks generally have a more relaxed process sequence where the order of individual process can be rearranged within certain limits to accommodate the availability of work stations. It is therefore that assembly processes are more suitable for free material flow as process sequence can be varied more easily.

Assembly and machining operations share the divisibility of processes into sub-processes (e.g. assembly of an oil pan is decomposed into applying sealant, placing the oil pan on the engine block, and securing it with several screws). For products and parts of medium to high complexity the duration for the shortest divisible subtasks differs significantly for assembly and machining. While the duration of the longest indivisible tasks in assembly processes is usually less than one minute (<1 minute), the shortest duration of machining tasks is one or more orders of magnitude longer (>1 or >10 minutes). Machining systems thus rely on parallel processes and have longer intervals between part transfers from machine to machine. Assembly operations on the other hand are more suitable for line balancing as their cycle times are shorter resulting in more frequent transportation.

Regarding manufacturing system design the key aspects to consider relate to the amount of individual items that need to be coordinated for each job, the time intervals at which transportation needs to take place, and the number of possible process sequences that can be laid out. Table 1 summarizes the key common and differentiating characteristics.

Table 1. Key common and differentiating characteristics defining manufacturing system design.

| Common Characteristics | Differentiating Characteristics |
|---|---|
| material flow between machines or work stations is based on transfer systems | fundamentally different operations inhibit the use of universal machines in assembly (e.g. joining versus machining) |
| process design defined by product complexity | cross-linked process sequence in assembly versus linear process sequence in machining |
| | more complex material flow in assembly as product and parts to be assembled require coordination (JIT, JIS) |
| | decomposing processes in smallest indivisible subtasks results in longer task durations for machining |

## 4. Review of Flexibility Paradigms

### *4.1. Comparison Framework*

The comparison framework is based on two axes, one covering the production level and one the object level that is being assessed. The production levels are based on [37] and cover the hierarchical levels of production network, factory, segment, line, and work station. The object level includes production resources, organizational aspects, and control/ scheduling within those production levels (see Fig. 2). The framework is designed so that evaluation criteria can be applied to more than one field in the resulting matrix.

Work stations refer to the smallest unit within an assembly or manufacturing system, e.g. work table or individual CNC machine. A line refers to a configuration of work stations and largely covers the degree of crossovers between them. The segment level is the highest production level relevant for short to medium term changes that can be addressed by the configuration of lines to one another (e.g. a final assembly lines and subassembly lines). The production levels of factory and production network are considered to be part of strategic changeability decisions and are not further addressed as this work, following the idea that the configuration of a manufacturing system is decisive for its suitability for lot size 1 and a high number of product variants.

Within the object level technical resources refer to all equipment within the manufacturing system, e.g. CNC-machines, transfer systems, assembly stations, and fixtures. Organization covers all aspects related to the interdependencies within a configuration. Lastly, control and scheduling includes all aspect regarding the monitoring of process status, production scheduling and control between work stations.

### *4.2. Overview on Assessment Criteria*

For the assessment of flexibility paradigms a total of 32 different criteria were defined and organized within the framework auf Section 4.1 (see Fig. 3). Criteria on the work station level address the work station's functionalities and its interaction with the product, those of the line level largely focus on material flow, and those of the segment level on relations between lines.

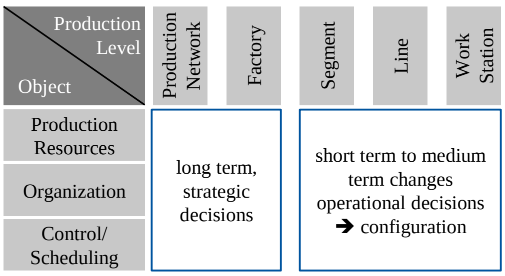


Fig. 2. Assessment framework for flexibility paradigms.

| | Segment | Line | Work Station |
|---|---|---|---|
| Technical Resources | | -transfer system<br>-material flow flexibility<br>-pallet design (transfer system)<br>-product identification | -tool use<br>-tool exchange<br>-handling systems<br>-supply (energy, aux. materials)<br>-disposal of aux. remains<br>-pallet design (product side)) |
| Organization | -inventory turnover<br>-capacity utilization<br>-area efficiency | -configuration<br>-throughput time<br>-decoupling<br>-robustness<br>-material flow<br>-capacity utilization<br>-area requirement | - method of material supply<br>-cycle time, station<br>-divisibility of processes |
| Control/ Scheduling | -status control<br>-scheduling principle<br>- JIT/JIS | -integration/ removal machines<br>-control of material flow<br>-status supervision | -standardization of process steps<br>-traceability<br>-integration/ removal modules |

Fig. 3. Assessment criteria.

### *4.3. Suitable Paradigms for Use in Industrial Assembly*

Each flexibility paradigm was described using the criteria listed in Fig. 3. Additionally, FAS and RAS were considered with both a low degree of automation (manual assembly) and a high degree of automation. To derive conclusions necessary conditions and sufficient conditions were defined:

- Necessary, derived from reconfigurability requirements [36]:
  - N1: ability to easily incorporate product variants,
  - N2: ability to easily scale the production volume, and
  - N3: ability to easily incorporate additional or changed technologies.
- Sufficient, derived from relevant characteristics of assembly and machining (see Table 1.):
  - S1: technical: ability to easily exchange process modules and adapt the degree of automation if required,
  - S2: technical: adaptability of transfer system configuration to accommodate changes in product structure and therefore sequence,
  - S3: organizational: ability to include processes of varying cycle time within one assembly system without fixed buffers, and
  - S4: ability to incorporate material flow for parts that are to be assembled to the main product.

The RMS principle, even though so far only known for machining applications, fulfils by definition the necessary conditions N1-N3. Condition S1 is met as entire work stations can be easily exchanged or added to the overall system. Exchange of modules within work stations is assumed to be addressed by RAS related research. S2 is also met by the premises of RMS transfer system design. The general ability to use the transfer system as a dynamic buffer also fulfils S3 for assembly systems. However, as RMS were designed for single part material flow S4 remains partially unfulfilled and poses significant challenges in scheduling and assembly system design that are addressed in Section 5.

## 5. Requirements for the Use of RMS Based Manufacturing Systems in Industrial Assembly

As stated in Section 4 RMS are not designed for complex material flow scenarios including the material flow for those parts that have to be assembled to the main product. As was described in Section 3 these parts are often of high value and are defining product variants by being sequenced parts. As such it is not feasible to store larger quantities of these parts at the assembly work stations. Doing so would increase the risk of assembling wrong parts or to disturb sequenced parts. The question of material flow leads to four research and development (R&D) areas that need to be addressed to make the RMS concept for machining viable for the use in industrial assembly. These are transfer system, logistics, scheduling, and interoperability (see Fig. 4).

As transfer operations within assembly systems are more frequent than within machining systems due to the limited parallelization of assembly work stations, a highly efficient transport logic is required to determine when to transfer which part or product and determine priorities at transfer system junctions. Accordingly, a transfer system topology model is required that can be used for efficient routing. Efficient omnidirectional transfer systems are an additional requirement.

To perform the scheduling of assembly tasks and their associated logistic operations for material supply, process time models are required to predict when a process will be done and a job will be transferred to another work station. Furthermore, a system behavior and influence model (e.g. number of buffer slots within the transfer system, length of transfer system, number of parallelized work stations) is required to assist during system design. Scheduling also needs to be highly dynamic to accommodate unexpected delays due to missing parts, defects, breakdowns.

Logistics requires the development of suitable material flow solutions that be used within the assembly system to provide the necessary parts at the right time and place. In conjunction with scheduling this requires a material flow prediction with a certain ‘warning time’ and accuracy so that the logistics department is able to deliver required parts without causing delays at assembly work stations.

Interoperability is the last requirement area focusing on a skill-based integration of work stations so that new work stations can be integrated at any time and are to announce their skills to the central scheduling system. This is the prerequisite to automatically assign jobs, provided these are described based on a skill catalog as well, to work stations. Furthermore, status monitoring is required to provide recent information on job progress and work station status to the scheduler. It is expected that such a skill-based concept can be based on existing research on plug and produce and RAS.

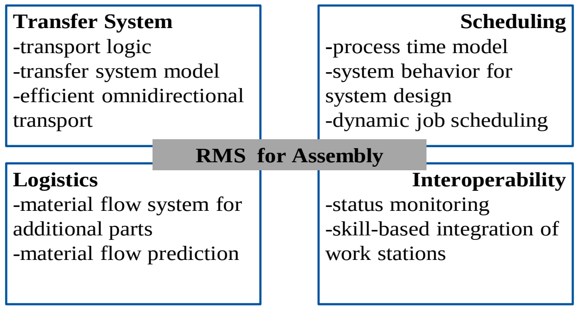


Fig. 4. R&D areas to enable RMS for the use in industrial assembly.

## 6. Discussion and Conclusion

Within this work it was concluded that the adaptation of RMS as designed for machining systems to the domain of industrial assembly appears to be feasible. This theoretic analysis is based on literature review and expert interviews and is part of ongoing research aiming to deploy according assembly systems. RMS-based assembly systems are without question not suitable for all applications. Beside the technical and organizational requirements of section 5, there are also limitations regarding the viability of specific production scenarios (i.e. average cycle time, product size, number of product variants, product complexity). It is expected that the concept is most viable for complex multi-model assembly lines with lot size 1. Further work will analyze the viability based on several case studies and simulation.

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