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Abstract. Reconfigurable manufacturing systems (RMS) emerged in literature during the last two decades with the aim to respond to the rapid increase in product demand and variations. The implementation of such solutions in the industry is very recent and remains difficult. In this article, an analysis of the industrial requirements and challenges involving four key aspects of RDSS (reconfigurability, digitalization, servitization and sustainability) is based on semi-structured interviews conducted with representatives from the industry. Further, the identified requirements and challenges are compared to those extracted from an extensive literature review. The findings of the comparison are divided into technology and organization oriented issues and show a strong interconnection of the four key aspects: Digitalization offers possibilities for the implementation of sustainable systems, servitization creates the possibility for companies to achieve more flexibility through reconfigurable systems and the further development of RMS offers more possibilities for digitalization and thus a better adaptation to current requirements.

Keywords: Reconfigurability, Digitalization, Servitization, Sustainability.

1 Introduction

Today's challenges in the manufacturing industry include the constantly changing requirements, a more volatile demand, increasingly varied products and new expectations in the field of sustainability. To meet these challenges, companies must deploy flexible and reconfigurable systems and operate them digitally within a network. Additionally, new business models and services can be applied. In [1] a framework was developed that shows the connection of digitalization, servitization and sustainability in the field of RMS. To apply the framework in the industry, it is important to understand the challenges and requirements that arise for companies when using reconfigurable, digitized, servitized and sustainable (RDSS) systems. For that purpose, semi-structured interviews were conducted and their results were evaluated on the basis of an extensive literature analysis. This paper provides an overview of the technologically and organizationally oriented issues of using RDDS and explores whether the literature and interviews agree or disagree. The authors also provide an outlook on the future research needed in the field of RDSS.

2 Related works

An RMS is defined as a system with several components that can be rearranged, moved and replaced quickly and reliably to adapt production in response to changes in market demand or technology [2]. This paper focuses on the requirements and challenges of digitalization, servitization and sustainability in RMS.

Reconfigurable manufacturing systems. RMS literature covers various areas, such as system design, process planning, scheduling and reconfigurable control [3]. One of the major issues found in the relevant literature is RMS design. The objective is to leverage their core characteristic (i.e. reconfigurability) to design responsive systems. For a system to be easily reconfigurable, certain characteristics such as modularity, integrability, convertibility, diagnosability, customization and scalability must be met [2], as well as automatability [4]. RMS design problems are more complex than those of conventional systems. This is due to (i) the system's dynamic capacities to change and to integrate change; and (ii) its properties, including reconfigurability, that emerge after the deployment of the manufacturing system [5]. The scalability of RMS is supported by adding or removing functionalities to maintain the lifecycle of the manufacturing system itself. To have the best responsiveness to change, system design must take into account reconfigurability from the outset [2]. The system perspective on production and design problems is favored for reconfigurability [4]. This implies that classical approaches will not necessarily lead to dynamically changeable systems. Besides, the designed system becomes quickly obsolete, when facing market variations, rather than achieving reconfigurability. Therefore, existing approaches and methodologies need to be adapted for designing systems with dynamic capacity by including the essential parameters for reconfigurability developed.

Digitalization of reconfigurable production systems. Based on the recent advancements in technologies in Industry 4.0 and digitalization, the development of RMS and modern manufacturing systems is entering a new era [6]. New technologies enable RMS to adapt quickly to changing conditions. Zangiacomi et al. derive from a case study on the implementation of Industry 4.0 strategies and methods in the manufacturing industry that the definition of company-specific strategies is needed to avoid standalone implementations of new technologies [7]. Koren et al. show that techniques for big data and cyber physical manufacturing systems can improve the design of RMS [6]. Based on advanced monitoring and analysis capabilities, intelligent real-time maintenance and production planning decisions can be made more effectively and intelligently. Nevertheless, current infrastructures are often not fully prepared to support digital transformation [8]. Based on new infrastructures, two current research-oriented approaches could yield operational results: (i) the exploitation of data science and analysis and their scalability in digitized production environments; (ii) the development of digital twin with value-added decision-making services [9]. Furthermore, manufacturers' security concerns, especially vulnerability to interference and cyber-attacks, increase with prevalence of increasingly digitized environments [10].

Servitization of reconfigurable production systems. Until now, scientific literature has developed the fields of manufacturing servitization and RMS as two distinct fields. Yet, a strong convergence can be highlighted. Brad and Murar underline that Product Service Systems and RMS share 'patterns towards similar goals', with RMS focusing specifically on manufacturing environments [11]. The convergence can be emphasized on three levels: The first level of RMS servitization considers the business model (BM) supporting the deployment of RMS. Determining and modeling key strategical aspects of the BM configuration is crucial for the design of reconfigurable systems. The second level is the system level, i.e. reconfigurability management at the level of a production segment, line or station. At this level, servitization of RMS leads first to taking into account that the overall functionality of any production system component involves both tangible technological components and intangible value-added of associated services and secondly, that the implemented services could ensure an optimum interoperability and reconfigurability of all the subsystems. Key challenges are associated with (i) digital interoperability of these subsystems [11], (ii) organizational management and planning of both manufacturing and service operations [12], (iii) modularity of both service and products, but also (iv) the need of decision-making solutions for managing the organizational performance of the changing configurations in an existing RMS. At a third level, RMS servitization has to be addressed at the operational level of manufacturing resource reconfigurability. This issue is more usual in literature [13], but key questions remain with regard to the adaptability of such solutions to small and medium enterprises and the integration of new artificial intelligence solutions, to increase the added value of manufacturing life cycle traceability.

Sustainability in reconfigurable production systems. In recent years, new objectives emerged for the design of production systems such as sustainability and reducing waste [14]. Faulkner et al. propose a methodology for improving the sustainability performance of a manufacturing line, which covers the three pillars of sustainability, namely economic, environmental and societal aspects [15]. More recently, [16] argues that RMS level of sustainability is an important aspect requiring investigation. Liu et al. study and model the energy consumption of a system as a multi-objective problem for sustainable RMS design [17]. The performance of the RMS is evaluated using criteria for energy-related costs, throughput and storage costs. Zhang et al. introduce the concept of energy-efficient RMS (REMS) and design a discrete event simulation model to evaluate the system's energy efficiency [18]. Meanwhile, the recent survey provided in [19] shows that if many possibilities can be addressed by RMS, as demonstrated in the literature, only a few research projects actually consider reconfiguration as an instrument for energy efficiency and sustainability in production.

3 Methodology

In order to better understand the industry's requirements and challenges regarding RMS, the authors conducted interviews with representatives from different industries in Germany and France. The structure of these interviews was derived from an analysis of the industrial needs and framework presented in [1]. The goal is to identify more precisely the needs of the industry for tools to help with the implementation and operation of reconfigurable systems. The survey focused primarily on four topics: reconfigurability, digitalization, sustainability, and servitization. Industry experts from 10 different companies were interviewed. The criteria of the quantitative research developed by [20] were followed to ensure valid, easy-to-generate, reliable, and objective results. The interviews were carried out in a semi-structured way, individually drawing out increasingly specific evidence regarding the interviewee’s assets. 6 out of 10 companies are active in the mechanical engineering sector, 2 in the automotive sector and 2 in the aerospace sector. The interviewees fill different positions in the companies, ranging from management to technical development as well as production planners and managers. 5 of the companies can be classified as providers of production systems, all being part of the mechanical engineering sector and 5 companies are users of production systems.

4 Results

Reconfigurability. The interviews showed that reconfigurability as a concept is known to most of the companies. All interviewees express the need for a flexible or reconfigurable production system in order to adapt to the quick changes in demand. However, the perception and level of maturity regarding reconfigurability varies significantly between the companies and mainly depends on the size of the company. While large companies are either pursuing extensive research in this field or are already using RMS production systems, mid-sized companies view reconfiguration more as the process of retrofitting, which is still often done manually. One interviewee, a provider of customized production systems, deals with machines very differently. As development costs cannot be shared among various customers or products, it would be too expensive to design each of these machines as reconfigurable ones. Other companies are trying to tackle this problem by modularizing certain functional parts of their machines to make reconfiguration possible. Other providers of production solutions, however, expect increasingly reconfigurable production systems in the future and adapt their services and products accordingly.

Digitalization. Regardless of their size, companies see potential in collecting and using production data. Such data are collected in order to optimize the production system, to forecast demand or to implement predictive maintenance. However, unreliable and unexploited data, low levels of digitalization and redundancy of the software used lead, especially for SMEs, to a considerable lack of holistic integration and to interface problems. The interviewees cite digital consistency as a main prerequisite for flexible production systems, whose degree of abstraction must be considered when dealing with

RMS. In addition, data security is a major challenge that still needs to be overcome, since the fear of excessive transparency in the transfer of sensitive data to third parties deters medium-sized companies from implementing digitization solutions. These problems make it difficult for large companies to further improve the level of digitalization among their customers. However, they also see economic potential for themselves, since many customers have a considerable need for further support in the transformation phase towards more digitized or even reconfigurable production. Model-based approaches are helpful, in which virtual models or digital twins are used to facilitate and support digitization efforts.

Sustainability. The conducted interviews also concerned the effects of RMS on the sustainability of production systems. The interest in sustainability aspects varies and depends on whether the companies are providing or using reconfigurable production systems. For users of reconfigurable systems, possible financial improvements resulting from the implementation of RMS on an operational level and the possibility of avoiding fines after regulatory changes are most important. Furthermore, being able to control the system's energy consumption and to schedule production in periods of low-cost energy are adding to both the economic and ecological potential. Additionally, RMS enable the socially appropriate alignment of employees' skills with the new tools of the production systems and externalization of highly specific skills by experts. On the other hand, providers increasingly emphasize the substantial impact RMS have on the sustainability of production systems, considering the whole lifecycle of production systems and the ecological impact of re-using production machines, in addition to economical and human viewpoints. It was thus observed that flexible/reconfigurable production systems are currently the most efficient way for large companies to fulfill the production program. Furthermore, the interviews highlighted the importance of developing metrics for measuring the sustainability of RMS. A return on investment indicator considering the possibilities posed by reconfigurability, a measure of costs and benefits from an ecological standpoint and a metric for reconfigurability potential could help decision-makers to adopt RMS.

Servitization. Many of the interviewed companies were familiar with the concept of servitization. However, most of the interviewed companies raised the concern of knowledge loss, which might arise in conjunction with servitizing certain parts of their production, as significant technological know-how might be exposed. If introduced, the companies would, therefore, start implementing servitized production processes in the field of secondary rather than primary processes. Furthermore, the technical prerequisites would have to be clearly defined. The companies did express a strong interest and would further consider it, especially if profitable use cases were presented. Other than that, two providers of production systems showed an interest in production management as a service. The first one seeks a closer relationship with its client by developing tools based on production data. The second one considers digital twins to be an opportunity to offer certain production management tasks as a service. Holistic approaches seem to be very difficult to develop because of the huge variety of possible tasks. However, digital twin solutions, which focus only on specific problems like bottleneck analysis, predictive maintenance or scheduling, could be more feasible due to the corresponding high complexity. For a smaller specialized provider, servitization is not attractive, as financial effort to keep their customers' production systems up to date would have to be underpinned by the company itself. The company currently benefits greatly from this circumstance by frequently selling new machines. The belief that manufacturing as a service leads to considerable cannibalization effects does prevail.

5 Discussion

Taking into account the results of the literature research and the interviews, a comparison between academic and industrial challenges is presented. The gap between these two visions is shown in Table 1, emphasizing that despite the shared vision of industry and academics on the importance of the four key issues, considerable work remains to be done to enable their consistent integration into business practice.

Table 1. Key factors relating to the gap between industrial and academic visions

Technology oriented issues	
RMS. All industrial companies are very concerned about flexibility and are aware of the challenges of reconfigurability, but RMS often seem not to be adapted to their proper context yet. The literature is mainly concerned with an elaborate complex design of RMS, but understandable and cost-effective systems are a key factor, especially for small companies. For some companies, flexibility through modularization is more feasible than reconfigurability.	**Digitalization**. Appears to be the topic most frequently addressed by the industry and the one with the least differences between literature and industry practice. There is a significant gap between the technical possibilities of future or current data-related technologies and the current basis for possible use. The interviews also showed a need for the development of new tools that enable software interoperability, especially for the integration of machines into old systems.
Organization oriented issues	
Servitization. Many companies integrate servitization in their market offer. Integrating it at the level of the inner industrial model with ‘manufacturing as a service’ is still at a very early stage of development. Especially large companies worry about the loss of know-how and are opposed to service models for primary activities. There is a lack of new relevant business model ideas here.	**Sustainability**. Shared agreement on the importance of research in sustainability, with two key industrial focal points (energy, competence). Sustainability is still considered as a secondary factor with no specific urgency. There is a lot of research on energy efficiency, but implementation is still poor. The potential of RMS to enhance sustainability remains unexploited in industry.

Other general conclusions can be highlighted. Firstly, digitalization appears to be a key factor for industrial/academic convergence and thus for further research into a new generation of RMS. Secondly, the four key concepts seem to be strongly linked. In addition, linking the aspects together may lead to the possibility of a further dimension. Digitalization offers possibilities for the implementation of sustainable systems, while servitization offers companies the possibility to create more flexibility through reconfigurable systems and further development of the technology RMS can create more possibilities for their digitalization and thus a better adaptation to current requirements.

6 Conclusion

This paper highlights the needs and challenges of the industrial application regarding reconfigurability, RMS digitalization, RMS servitization and RMS sustainability, comparing them to the ones referred to in the literature. The strong interconnection of these four topics and their complementarity makes it a strong value added for further research steps. With acceptability and adopting practices being two of the main concerns for companies, it is a significant requirement for research and will necessitate to demonstrate increases in performance over the entire lifecycles through suitable indicator systems and specific demonstrators. An in-depth analysis of both the literature and the industrial interviews will be used to update the framework previously presented in [1], in particular by focusing on the requirements of decision support tools with the aim to be used as a research roadmap.

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