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Abstract. The concept of the Reconfigurable Manufacturing System (RMS) was introduced for the first time almost 20 years ago as a new manufacturing system concept with functionality and capacity being dynamically changeable through modularity, integrability, diagnosability, and customization. Since its introduction, the RMS concept has been extensively researched from various perspectives and new trends are today increasing its relevance. This research revisits the current status of both RMS research - in terms of research domains and trends - and RMS practice - in terms of potentialities and limitations towards broad industry application. Based on this, a design methodology in four steps is proposed and, to ensure its industry-applicability, the existence or lack of tools for each step is summarized as a basis for future research developments.

Keywords: Reconfigurable manufacturing system, Changeable manufacturing, Reconfigurability, Design methodology.

1 Introduction

The concept of the Reconfigurable Manufacturing System (RMS) was initially introduced by Koren in the late 1990's with the aim of providing capacity and functionality on demand and as an intermediate paradigm between the Dedicated Manufacturing System (DMS) with rigid structures and high efficiency and the Flexible Manufacturing System (FMS) with high in-built a-priori flexibility [1]. Today, the concept both maintains and increases its relevance in education, research and practice [2-4]. Furthermore, new and additional competitive factors going beyond rapid responsiveness and lower cost motivates RMS in today's manufacturing environment [5], e.g. in relation to environmental performance aspects such as recycling, de-manufacturing and re-manufacturing [6, 7] and in regard to implementation of smart manufacturing and industry 4.0 related technologies [3, 8].Therefore, this research revisits the RMS paradigm from both academic and practice perspectives. In particular, the contribution focuses on: (i) outlining dominant research domains and trends in relation to reconfigurability, (ii) evaluating current relevance and limitations of industry application, and based on this (iii) proposing a four-step RMS design methodology to aid the wider industry transition and provide a basis for future research developments.

2 RMS in Research: Dominant Research Domains and Trends

Since the RMS concept was coined, RMS and "reconfigurability" – or equivalently "changeability" at factory and firm levels - have received broad attention in research.

2.1 The two Domains of Research on RMS

Overall, there are two domains covered by literature; these are: (i) the design and (ii) the operations (and management) of such systems. Examples of research on RMS design include design methodologies [9, 10], economic evaluation of reconfigurability [11, 12], design of reconfigurable machines [13], reconfigurability characteristics and their implementation [14], and identification and modelling of platforms as a foundation for reconfigurability [15, 16]. Operational issues include process plan generation for reconfigurable systems [17, 18], configuration selection problems [19, 20], reconfiguration management [21] and scalability planning [22, 23].

In their traditional interpretation, RMSs are highly automated systems composed of CNC machines and/or Reconfigurable Machine Tools. More recently, RMSs have been more extensively interpreted as systems enabled by a multitude of aspects that can be designed and operationalized in a vast array of company and context specific forms [4, 24].

Literature reviews have also been conducted (e.g. [3, 25]) remarking that both the design and operation domains need further research. The main conclusion similar in all reviews is the need for practical guidelines driving industrial companies in the transition toward the RMS paradigm. Indeed, the implementation of RMS is still an open issue to the manufacturing professionals [25]. Case studies and best practices efficiently driving the transition of modern industrial companies toward RMS are needed [3].

2.2 Reasons for the Increase of Interest in RMS

There are two additional reasons for RMS to keep and increase its theoretical importance around 20 years since the introduction: (i) its relevance to deal with the paramount need for manufacturing companies to consider sustainability issues [7, 26] and (ii) the potentialities represented by the inclusion of more recent digital technologies into the RMS paradigm [27, 28]. Regarding sustainability, higher reconfigurability of manufacturing systems leads to better environmental and economic performance, as well as to reduce the energy consumption [3]. RMSs are emerging as one of the most popular manufacturing strategies to achieve sustainable manufacturing [7]. Indeed, RMSs can achieve high system sustainability thanks to their capability of producing multiple generations of products [5].

Regarding digital technologies, recent development of advanced diagnostics and cyber physical manufacturing systems can facilitate the design and operations of RMS [5]; Cyber-Physical Systems have been proposed in the manufacturing area as suitable technologies for supporting rapid reconfiguration and system evolution at shop floor level [27]. Despite the interesting insights, there is still a lack of literature focusing on the synergic relationship between RMS and Cyber-Physical Systems [3].

3 RMS in Practice: Potentials and Limitations

The authors of this paper have previously conducted a survey [29] of manufacturing companies, analyzing the potential of implementing RMS, as well as the barriers towards this. The general conclusion of this study was that few of the companies had skills and competences in place for developing RMS. Some differences were identified in terms of the readiness for developing reconfigurability in the different cases, which seemed to relate to which industry they were operating within, where electronics manufacturing seemed to have the highest degree of coordination between product design and manufacturing system design, which is essential when developing RMS. Furthermore, applying a long-term view when planning manufacturing system development and economically justifying them was observed in some companies but not others. The presence of enablers of reconfigurability was also analyzed. Generally, most companies had only few or none enablers present. Also, the companies generally recognized that their current level of the enablers was lower than what was actually needed to achieve the desired level of reconfigurability. The presence of specific enablers depended somewhat on different characteristics of the companies.

In another more recent study from the same authors, eight different cases were analyzed, addressing companies that were currently doing development or implementation of reconfigurability [30]. This study analyzed the potentials in doing reconfigurability across the cases. In all cases it was found that reconfigurability did in fact hold a potential, however, on different levels and time frames. For example, low volume, high variety tended to have more potential in operational reconfigurations on short term, whereas higher volumes tended to have more potential on tactical and strategic level for reconfigurability. Due to these differences, the enablers that would enable reconfigurability in the different cases were also widely different. This clearly influences how reconfigurability should be developed in these companies, and contributes to the point that not one generic set of enablers can be applied to all companies, and thus not one single RMS development methodology can be applied to all companies, and therefore a context dependent method should be introduced.

4 Towards a Design Methodology

As both research and practice suggest the need for practical and context dependent guidelines driving industrial companies in the transition toward the RMS paradigm, a RMS design methodology is proposed in this section.

The suggested methodology is based on a generic design methodology provided by Andersen et al. [2], which has been chosen for two reasons: (i) it is academically relevant, as it is built based on literature and (ii) also it attempts to support practitioners, providing a mapping of the different design challenges, suggested procedures, and applicable tools. The suggested RMS design methodology involves four steps consisting in several activities as shown in the figure below (Fig. 1); to ensure its applicability in industry, in each step, specific tools should be provided. In this section, some representative tools available in literature have been associated to individual steps and those not covered by specific tools have been identified as needing further research. The methodology is described in the remainder.

Step 1. Classification of potential and goals. This step covers planning and making strategic decisions about the development project. A major challenge in this step is the life-cycle perspective and the uncertain nature of predictions [2]. Scenario analysis should allow for getting insight into the real-market uncertainties, by considering market demand stochastically and not deterministically [25]. The definition and monitoring of KPIs based on measures of characteristics of reconfigurability could support the evaluation of system structural performance [31, 32]. To quantify the potential in RMS compared to conventional manufacturing systems, scenario analysis and participatory approaches should aim at involving firms in the definition of future production requirements and the corresponding most suitable manufacturing paradigms [9, 14]. For each consistent scenario of the future, the projected factory should be analysed to draw conclusions about the evolution of the objects in the factory and their cost-effectiveness [33]. Requirements should be well analysed and described, also recurring to conventional planning tools (e.g. requirements list) [34]. Finally, to prioritize objectives and requirements, the Analytical Hierarchy Processing method could be used [10, 35].

Step 2. Development of concept for reconfigurable production. At this stage, decisions should ensure that both product and manufacturing processes are designed for reconfigurability and that the two designs are adequately related with each other. In recent years, digitalization throughout the entire Product Lifecycle has allowed manufacturing companies for significant coordination gains between product and production system design, holding the potential of elevating companies to reach new levels of reconfigurability. One of the main challenges related to that is the effort in promptly updating the information when the system needs to be reconfigured. To ensure the adequate design of products, products should be classified based on either their morphological or technological features, clustering techniques or visual inspection can be used to this end [36]. Bill-of-Materials trees and a tree dissimilarity measure can be used to allow matching integer programming model to address commonality of products and form product families [37]. To ensure reconfigurability, products should then be grouped based on production flow features. Techniques such as the Rank Order Clustering algorithm or the use of similarity coefficients [38, 39] are the most widespread to this end. Based on company-specific data and following an iterative (and collaborative) approach, the relationship between the manufacturing system and its respective products can be studied and integrated product-process (object-oriented/functional) modelling can be achieved [40, 41]. The use of tools such as axiomatic design techniques and function-means formalism allow for achieving maximum possible decoupling of functional requirements based on existing functional requirements and the future functional requirements in order to enable a minimum of functional change when changes occur [36]. In this step, the definition of production platforms, i.e. sets of manufacturing subsystems developed to form a common structure from which a stream of products can be efficiently produced [40], is an important enabler of reconfigurability [41]. To define such platforms, a classification scheme of manufacturing systems [42] and functional modeling [40] are appropriate tools. Decisions on manufacturing modules and granularity level can be made using tools such as Design Structuring Matrix and Cladistics [36, 43]. Finally, the definition of KPIs and the use of visualization tools allow for evaluating different design concepts [35].

Step 3. System design. This step is industry-specific and may need the definition of general tools. The implementation of a function-driven object-oriented methodology [44] supports the following activities. First, the reconfigurability needs should be defined. Second, an evaluation of the existing manufacturing setup to identify primary functions, terminal functions and possible suited modules should be performed. The identified modules are to be included in the system design and should be modelled and simulated, to evaluate the design solution candidates through a trade-off analysis between reusing existing modules and designing new modules [45]. Third, existing modules - either internally developed at the company and/or commercially available - should be classified through a module tree analysis [46]. A structural tree of the modules evaluates the constraints in reconfiguring the modules. The function tree, the module tree and the structural tree yield a module library from which industry specific RMS design prototyping is enabled. Finally, in this step, the right technology should be selected and the degree of automation for each operation should be defined.

Step 4. Anchoring/ Realisation. This step consists in the detailed design of the RMS. As the previous one, this step may need the definition of general tools. Moreover, issues such as the integration design of systems can be very case-specific, making the generalization of tools even more challenging. Overall, this step needs detailed specifications and documentation from the previous step, especially if the actual development of new modules is outsourced to technology suppliers. Furthermore, tools to optimize ramp-up procedures and quickly operationalise implemented changes are paramount to ensure cost-effective reconfigurations over time.

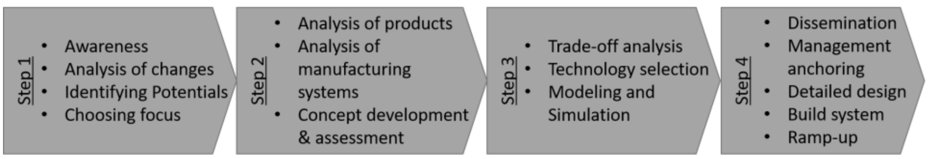

Fig. 1. Four-step methodology to design RMS

Overall, the first two steps of the RMS design methodology proposed are well represented by tools already available in literature, the remaining two steps deserve further investigation to enable companies to use the proposed methodology.

5 Conclusions and Future Work

This research proposes a methodology in four steps to design RMS. The methodology is based on available literature and considers the need of practitioners for context dependent guidelines. To ensure its applicability in industry, further research is needed. Indeed, the suggested methodology needs to be consolidated through the identification of relevant and industry-applicable tools for each individual activity (see Fig. 1) of the four steps and how they affect the characteristics of reconfigurability, as well as effect on sustainability and digitalization. Furthermore, many activities might require an adaptation of the already available tools or even the creation of new adequate and hopefully generalizable tools.

To pursue this objective, further research is needed. Above all, collaborative projects with companies might provide valuable insights to ensure the applicability of the method in industry.

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