Planning the reconfiguration of manufacturing systems: a literature review

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Abstract: The diffusion of Reconfigurable Manufacturing Systems (RMSs) is envisioned as a potential lever for manufacturing firms to gain competitive advantage. In fact, responsiveness is required in the current context characterized by unpredictable frequent market changes and demand for increasingly individualized products with shortened life cycles. Reconfigurability is a well cited capability because it promises to allow high responsiveness. Many authors point out that, to be really market-able, RMSs need to have convenient reconfiguration time and cost. To this end, a great synergy between the reconfigurability and the process of planning the reconfiguration should be exploited: this is the main reflection that the present paper is bringing based on a literature review. More in details, the paper describes the characteristics of reconfigurability; besides, it elaborates on the reconfigurability as a capability, having a particular focus on the scalability characteristic and its relationship with the planning process. The reflection provided in the paper allows to get an overview of the need to structure the process of planning the reconfiguration within RMSs.

Keywords: reconfigurable manufacturing systems, reconfigurability, scalability, planning the reconfiguration.

1. Introduction

Nowadays manufacturing firms are facing a big challenge trying to survive in the current context characterized by unpredictable frequent market changes and the demand for increasingly individualized products with shortened life cycles (Koren et al., 2016). For this reason, responsiveness (i.e. the ability to react quickly) at an affordable cost is today a decisive competitive advantage (Mehrab, et al., 2000).

To date, not all manufacturing firms seem able to properly handle the actual challenges. For this reason, many researchers point out that manufacturing firms are undergoing an evolution in order to achieve their goal of improving responsiveness (see, for instance, ElMaraghy, 2014). This trend is supported by many technological advances which are promising big changes in manufacturing. Amongst them, Reconfigurable Manufacturing Systems (RMSs) and reconfigurable components are seen as a real alternative to “traditional” systems. Using the words of Koren (2006), a RMS is “a system designed at the outset for rapid change, in order to quickly adjust production capacity and functionality within a part family”.

A great deal of interest around Reconfigurability has been showed in literature since nineties, and this interest has increased over the last couple of decades. RMSs can be seen as the solution to the inappropriateness of the actual “traditional” manufacturing systems. RMSs allow “evolving/customized” flexibility. In other words, according to their concept, they provide exactly the functionality and the capacity exactly when needed because they can be adapted over time to the new requirements. Conversely, Flexible Manufacturing Systems (FMSs) allow “general” flexibility (Wiendahl et al., 2007): investing in FMSs means to buy a system that is not designed to be adaptable through time, even if capable of performing a wide variety of processes. Many proponents believe that RMSs could offer a cheaper solution in the long term, compared to “traditional” solutions like FMSs, as they can increase the life and utility of a manufacturing system (Wiendahl et al., 2007) due to the capability to reconfigure through time (aligning to the concept of “evolving/customized” flexibility).

In turn, and more recently, reconfigurability is enabled by the availability of smart technologies (Negri et al., 2016; Fumagalli et al., 2014). The possibility to have decentralized intelligence or, in other words, to have a manufacturing system characterized by the presence of networked objects with computing capability integrated with communication capability allows to envision a better digital control and upgrade of the system components (Energetics Incorporated, 2012; Garetti, et al., 2015). This would be relevant in order to open to many relevant characteristics for production management (in terms of capacity management and customization) as well as maintenance and quality management.

Indeed, it is clear that today the technological innovation brings potentialities to face the actual challenges and let manufacturing firms improve responsiveness. However, technology by itself is not enough: it has to be properly managed. To support this concept, we can remark also the
evidence that, in the recent years, reconfigurable training factories in many centres of excellence have been built: they are provided with the innovative technology required for RMSs. Nonetheless, in these training factories, researchers are cooperating with industry partners in order to improve the knowledge and capabilities of industrials and let the diffusion of this kind of innovative systems. We interpret it as a result of an effort to bring into practice such new technology concepts (related to RMSs together with smart technologies). As it happens, research agendas, in production, maintenance and quality issues, will be re-written, and management would play a relevant role in this regard.

In this paper we reviewed part of the literature referred to RMSs, using it to highlight the aforementioned concept, thus discussing the need to plan the reconfiguration of manufacturing systems. In particular, to properly deal with the reconfigurability as a capability of a manufacturing firm, we concentrate on the need of manufacturing firms to structure a process to plan the reconfiguration within RMSs.

2. Literature review

Many authors point out that, to become really marketable, RMSs need to have convenient reconfiguration time and cost. Using the words of Zhang et al. (2006) the reconfiguration time is the period of time taken by system reconfiguration (it is the time required to redesign the system, build machines, re-arrange the equipments...). Hence, reconfiguration time can be seen as a cost (i.e. opportunity costs) since it affects the service level due to the losses related to the reconfiguration period (Zhang, et al., 2006). Thus, the reconfiguration cost can be seen as the cost incurred to redesign the system, build machines, re-arrange the equipments...).

2.1 Definitions

Reconfigurability as a capability has been widely studied in literature. According to literature, it can be decomposed into six core characteristics: modularity, integrability, customization, convertibility, scalability and diagnosability.

The definitions of the six characteristics have evolved and have been enriched over time (Mehrabi et al., 2000; ElMaraghy, 2006; Bi et al. 2008; Koren, 2016). Hereafter, we wish to report these definitions, trying to synthesize and to structure them, exploiting the various contributions over time; besides the definitions, the benefits of each characteristic are reported according to the literature (whenever such benefits are explicitly stated in the referred papers).

Modularity: system and system components, both software and hardware, should be modular, or, in other words, they should be combinable with each other. Modules are easier to manage and to update than whole machines, giving the system the possibility to continuously evolve.

Integrability: system components should be easily integrated not only with each other, but also allowing future introduction of new technologies. Then, integrability is the ability to integrate system components rapidly and precisely by a set of mechanical, informational, and control interface.

Customization: the dominant features of the part family being manufactured should determine the overall configuration of the system and of the system components. In other words, customization is the ability to adapt the flexibility of production systems and machines in order to meet new requirements within a family of similar products.

Convertibility: it is the ability to easily transform the functionality of existing systems and system components to suit new production requirements.

Scalability: it is the ability to easily change (increase or decrease) existing production capacity by rearranging the system, and/or changing the production capacity of its components (e.g. machines).

Diagnosability: it is the ability to quickly identify the sources of quality and reliability problems that occur in a system and subsequently correct them.

In general, the six characteristics of reconfigurability allow the reduction of the reconfiguration time and cost.

Modularity and integrability, being associated to a specific instant, can be considered “characteristics” of the components of the system. Conversely, customization, convertibility, scalability and diagnosability, being associated to a time interval, can be considered “abilities” of the whole system.

2.2 Interpretation

The six characteristics of reconfigurability are not just enabled by the exploitation of technological innovation, but also by their proper management. In the remainder, we aim at reflecting on such technology - management relationship.

In the below table (Table 1), some interesting references are classified according to their focus on either technological or managerial aspects of the various characteristics:

<table>
<thead>
<tr>
<th>Requirements Characteristic</th>
<th>Technological innovation</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modularity</td>
<td>(Garetti et al., 2013)</td>
<td>(Koren, 2006)</td>
</tr>
<tr>
<td>Integrability</td>
<td>(Negri et al., 2015)</td>
<td>(Zuehlke, 2010)</td>
</tr>
<tr>
<td>Customization</td>
<td>(Shaik et al., 2014)</td>
<td></td>
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<tr>
<td>Convertibility</td>
<td>(Koren, 2013)</td>
<td></td>
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<tr>
<td>Scalability</td>
<td>(Niroomand et al., 2012; 2014)</td>
<td></td>
</tr>
<tr>
<td>Diagnosability</td>
<td>(Fumagalli et al., 2011)</td>
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Within the review, we identified a reasonable and direct link between the process of planning the reconfiguration
(or, more specifically, planning the scalability) and the scalability characteristic. Thus, we mainly focused on the review of the literature concerned with scalability. Moreover, the interest showed by literature to this characteristic gave us a good reason to focus on it.

Many insights were derived from the works of Deif and ElMaraghy; Niroomand et al., 2012, 2014; Koren et al., 2016. We wish to report their citations, in order to highlight the common will to remark the need to plan the reconfiguration of manufacturing systems.

In 2007, Deif and ElMaraghy identified the need to reduce the delay in achieving the required scalability, saying that “more effort, on both the technical as well as the managerial levels, is required to decrease the delay in achieving the required scalability to enhance the responsiveness of RMS”. Their paper presented simulation results and analyses in order to help “capacity scalability planners” (using their terminology) in RMSs to investigate the best scalability policy for various demand scenarios. They highlighted the need to plan, remarking that, although the basic philosophy of RMSs is to exactly match the demand, the demand chasing scalability policy was not the best policy to be adopted in their experimentation.

Niroomand et al. (2012; 2014) reviewed the literature referred to what they called “capacity planning models” that incorporate capacity scalability. While doing so, they differentiated the literature referring to “strategic, tactical, and operational” levels. They also investigated the optimal allocation of capacity investments at the tactical decision-making level by incorporating the configuration characteristics into the decision making process. Hence, they tried to deal with the aforementioned need to plan (in this case need to plan scalability) and, in particular, they highlighted the need to plan in a certain time horizon (then, they mainly focused at tactical level).

For Koren et al. (2016), scalability enables to design the system structure for changes in order to modify its capacity in response to market changes. By better contextualizing this expression, we can say that, with “design … for changes”, the authors refer to a process of planning scalability. Again, the need to relate scalability to the process of planning arises.

Recognizing the dependence of the process of planning the reconfiguration on the time horizon, we reviewed also papers that were more concerned with the short-term, focusing on decisions affecting the immediate future. In fact, within the immediate future, planning the reconfiguration can be seen as the coordination and the control of the system components. It is worth remarking that, for the sake of clarity, within this paper we often interchange the words “coordination” and “control”: for our scope, we can assume that coordination and control have the same meaning, more in detail coordination could be defined as “dynamic control”. To understand better this assumption, see Zhang et al. (2015).

Many researchers identified gaps in the development of control systems (Bi et al., 2008). In line with our reflection, many authors also highlight that control systems could allow to improve the scalability capability (see Deif and ElMaraghy, 2007). Thus, the need to relate scalability to the process of planning is confirmed also with respect to control tasks in the short-term.

Even without further deepening the study of the other characteristics (i.e. modularity, convertibility, integrability, customization and diagnosability), many important studies referred to the reconfigurability in general or, in particular, to some of the other characteristics helped in corroborating the conclusions of this paper. For this reason, we wish to report these additional insights, by using some selected references.

Having a general perspective, in 2016, Puik et al. (2016) wrote that “the reconfiguration ‘scheme’ of a RMS needs to be carefully investigated ahead to find the adjustment of the system that adequately matches production demand. (…) A method for inventoring and quantification of risks in the reconfiguration process could help to find the right balance in optimisation on the short, the mid, or the longer term”. Again, even if the authors did not refer to a specific characteristic of reconfigurability, they pointed out the necessity to contextualise the need to plan the reconfiguration in a certain time horizon, and the necessity of specific methods to support planning.

The relationship between the reconfigurability and the process of planning and coordinating the reconfiguration is interesting also because it is not banal, in the sense that reconfigurability introduces complexity that requires to be properly managed. This is witnessed by Bruccoleri et al. (2005) who pointed out that, due to the reconfigurability capability, a great deal of complexity is introduced in the planning and scheduling processes. In their opinion, the coordination between the elements of the network is a challenging issue involving distributed problem solving tasks. Even Bi et al. (2008) remarked the complexity introduced by reconfigurability, pointing out that effort should be put on “how to coordinate modular components to achieve system objectives efficiently”.

Referring to convertibility, in 2013, Koren identified the need for practitioners to find a way to measure and quantify convertibility in order to compare system configurations during the early phases of design without requiring detailed product or process plan information (Koren, 2013). Moreover, convertibility has been defined by Koren (2006) as the counterpart characteristic of scalability. Putting these insights together, we understood that, even on a long-term time horizon (i.e. at design stage), different configurations need to be compared (i.e. a plan is needed) and the degree of convertibility should be measured in order to choose the alternatives which ensure better reconfiguration performances (i.e. time and cost).

Referring to integrability, Zuehlke (2010) pointed out that we should create and apply standards (then, in other words, integrability is needed) to all levels of the
automation pyramid (reported in Figure 1), in order to reduce planning effort and allow re-use of components. We can say that “scenario analysis” is a strategical activity of planning the reconfiguration. Due to the uncertainty of the context, it consists in comparing possible realizations of future events and choosing the right actions in order to reach a long-term goal. We wish to give some examples referred to the “scenario analysis”: (i) making the decision to design a system with empty spaces, located in properly selected locations, to face likely changes in demand in the long-term; (ii) or investing in a material handling system, to be ready to adapt handling in new reconfigurations; (iii) or investing in a scalable machine and/or providing it with scalable modules.

We can define “planning” as a tactical activity of planning the reconfiguration. It consists in setting the right activities in order to reach a short/middle-term goal. More concretely the tactical “planning” means to make the decision of rearranging a system to deal with changes in some requirements, for instance acting on the production capacity of machines by picking scalable modules from a set of alternatives.

Eventually, we define “coordination” as the operational activity of planning the reconfiguration. It consists in being able to make decisions instantly in order to reach an immediate/imminent goal. For example, arranging the quick setup of the machines.

4. Conclusions

The main conclusion that can be derived from this literature review is the fact that, within manufacturing firms, the changes generated by technological innovation leading to RMSs cause transformations in managerial requirements. Effectively, to meet the actual changeable market requirements (i.e. to improve responsiveness), not only technology but also management of the operations is a relevant enabler. In particular, the process of planning the reconfiguration of manufacturing systems should be structured, since it is a critical process to improve the reconfigurability capability. The reasons for criticality can be summarized as follows: (i) the actual unpredictable context forces firms to quickly react, and planning is a way to answer to this need; (ii) the actual availability of smart technologies brings potential to improve the decision making processes (i.e. “planning the reconfiguration” constitutes an example of decision making process) and, consequently, to improve responsiveness.

Focusing on the perspective of benefits, structuring the process of planning the reconfiguration could reduce the reconfiguration time and cost. Specifically, in the discussion referred to scalability we identified a close relationship between scalability and the process of planning the reconfiguration: improving the latter means improving the scalability capability, which results in better reconfiguration time and cost, thus better responsiveness (thus finally allowing to gain competitive advantage).

On the whole, within this literature review, we identified a direct relationship between scalability and the “planning-variable”, related to time. We also placed insights referred to other characteristics of reconfigurability. Nonetheless, we believe that literature review has to be enriched to

Thus, there is a relationship also between planning and integrability, even if it is an indirect link. In this case, in fact, integrability is limiting the effort needed to plan reconfigurability. In other words, taking an overall view, we could consider also the interdependence between integrability, planning, scalability, and convertibility: integrability impacts on planning which, according to the previous concerns already remarked, deals with scalability and convertibility. Next Figure 2 synthesizes this concept as initial hypothesis, useful in order to frame the process of planning the reconfiguration in manufacturing systems.

![Figure 1 Automation pyramid (Zuehlke, 2010)](image)

3. An attempt to frame the process of planning the reconfiguration of manufacturing systems

Our literature review has led to recognize the dependence of the process of planning the reconfiguration on the time horizon. (see Figure 3).

![Figure 2 Hypothesis on the relationship between the characteristics of reconfigurability and the process of planning the reconfiguration](image)

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![Figure 3: The planning process, related to the time horizon](image)

Planning the reconfiguration is a decision making process. Thus, according to Figure 3, we assume that, depending on the length of the time horizon, this process can be: either scenario analysis, or planning, or coordination.

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understand the relationship between the planning variable and the six characteristics of reconfigurability. We are also convinced that this study should be deepened and accomplished by empirical evidences and experimentation on real cases.

References


