Core Characteristics of Reconfigurability and their Influencing Elements

Alessia Napoleone*, Alessandro Pozzetti*,
Marco Macchi*

* *Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milano, Italy*
(Tel: 0039 02-2399- 4763; e-mail: alessia.napoleone@polimi.it)

Abstract: The unpredictability of market requirements is more and more pushing manufacturing firms to be responsive. To this end, reconfigurability is needed. Reconfigurability is composed of six core characteristics: modularity, integrability, diagnosability, scalability, convertibility and customization. These characteristics are related with each other. This paper – exploiting the available literature – aims at identifying and analyzing elements influencing the core characteristics. As a result, characteristics, influencing elements and relationships have been located in a comprehensive framework. The novelty of this research is that the relationships between characteristics have been taken into account. For this reason, this research is considered a first step to understand how manufacturing firms can achieve reconfigurability, by fully exploiting the core characteristics.

Keywords: reconfigurable manufacturing systems, characteristics of reconfigurability, reconfigurability elements, reconfigurability framework.

1. INTRODUCTION

Unpredictable market changes and the sharp reduction of product life cycles are currently challenging manufacturing firms (Koren et al. 2016). In this scenario, responsiveness, i.e. the speed at which a system can meet changing goals at an affordable cost (Koren & Shpitalni 2010; Mehrabi et al. 2000), is more and more a decisive competitive advantage (Shaik et al., 2014). According to literature, reconfigurability, i.e. the ability to repeatedly change the components of a system in a cost-effective way to meet new changes (Rösiö, 2012), is needed in order to be responsive (Shaik et al. 2014; Goyal et al. 2013). It is well recognized that reconfigurability is composed of six core characteristics: modularity, integrability, diagnosability, scalability, convertibility and customization (Mehrabi et al., 2000; Wang et al., 2016). For their descriptions see, for example Bi et al. (2008), Chaube et al. (2012) and Koren (2013). The relevance of these characteristics lies in the fact that they allow reducing reconfiguration time, cost and ramp-up time (ElMaraghy, 2006; Koren, 2013).

Exploiting the extensive body of literature on reconfigurability characteristics, the objective of this paper is to identify elements influencing the six core characteristics and locate them in a comprehensive framework. To this end, the paper is structured as follows. Section 2 reviews the available literature analysing reconfigurability characteristics. Section 3 proposes a qualitative framework of characteristics and their influencing elements. Section 4 draws main conclusion and future projects related to the topic.

2. LITERATURE REVIEW

This section reviews the available literature analysing reconfigurability characteristics. It is focused on the analysis of characteristics-related elements. Relationships between these characteristics have been taken into account.

Wang et al. (2016) analysed the meaning of each characteristic and established a model for the calculation of indexes to evaluate them. To Farid (2014) integrability, convertibility, and customization are composite measures that can be derived starting from two kind of reconfigurability measures: reconfiguration potential and reconfiguration ease. Gumasta et al. (2011) decomposed modularity, diagnosability, scalability and convertibility in multiple measures. Liu et al. (2004) built a diagnosability matrix model to delineate the relationships between attributes of quality monitoring and fault diagnosis. Maier-Speredelozzi et al. (2003) proposed metrics for using convertibility to compare system configurations during the design stage.

With regard to the relationships between characteristics, Napoleone et al. (2018) built a literature-based framework, stressing that:

- Modularity and integrability influence scalability, convertibility and diagnosability.
- Diagnosability influences scalability and convertibility.
- Scalability and convertibility influence customization.

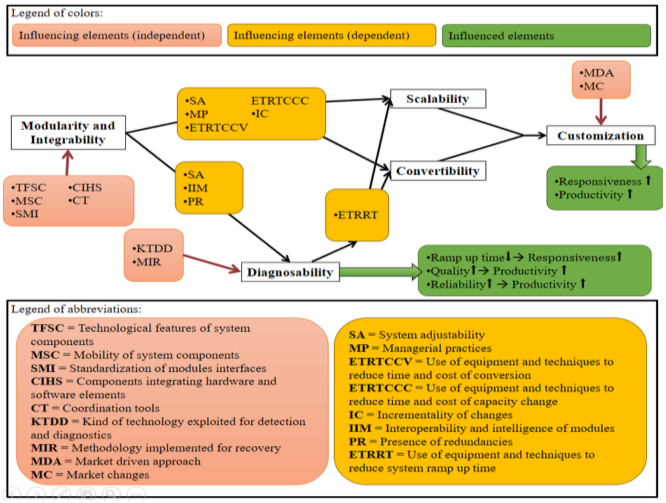
Indeed, measures of reconfigurability should take into account characteristics-related elements and relationships. Therefore, in the following section the available literature has been exploited to identify constituent elements of characteristics and locate them in a comprehensive framework. Especially, such framework is based on references proposing quantitative measures of reconfigurability. This research can be considered a first step to better understand how manufacturing firms can achieve reconfigurability. Measures of reconfigurability would be a follow-up.

3. FRAMEWORK OF CHARACTERISTICS AND IINFLUENCING ELEMENTS

This section describes the building process of the framework showed below (Fig. 1): elements related to characteristics and their relationships have been identified, summarised in abbreviations and theoretically justified. The elements have also been classified in:

- influencing elements. In turn, these are divided in: (i) independent, i.e. influencing one or more characteristics and not influenced by some others; (ii) dependent, i.e. elements influencing one or more characteristics and influenced by some others;
- influenced elements.

Fig. 1. Framework of characteristics and elements



Furthermore, reference has been made to system, intending the set of interlinked subsystems made of groups of workstations and material handling devices used for manufacturing variants of a part or a product family. Subsystems can be either cells, lines or production departments.

3.1 Modularity and Integrability

Modularity and integrability are closely related (Shaik et al, 2014; Mehrabi et al., 2002). Indeed, according to Mehrabi et al. (2002), the ability to integrate/remove new modules without affecting the rest of the system is a key enabler of reconfigurable manufacturing systems. Modularity and integrability should ensure the autonomy and independence of system components. For Wiendahl et al. (2007), modules are autonomously working units that ensure a high interchangeability with little cost or effort. To some authors this is the reason why modular structures are cost effective: systems are focused around parts to be produced, with the possibility to be changed over time (Abdi 2009a; Chaube et al. 2012; Deif & Elmaraghy 2007.

The independent elements influencing modularity and integrability, are illustrated below.

- Technological features of system components (TFSC). Rehman and Subash Babu (2013) referred to the technological level of system architectures influencing reconfigurability. Abdi and Labib (2004), referred to the level of automation of the system as influencing element of scalability and convertibility. However, the level of automation is closely related to physical system components, thus it directly influences modularity and integrability and indirectly influences scalability and convertibility.
- Mobility of system components (MSC) (Mesa et al. 2014; Abdi 2009b). Mobility is the easiness of moving around and relocating modules and subsystems (Rosio, 2011). For Abdi (2009b) mobility is one of the criteria influencing layout reconfigurability. According to some authors (Elmaraghy, 2006; Rosio, 2011), mobility influences scalability and convertibility. However, within our framework, the possibility to move system components is paramount to organize the system in autonomous entities, having a specific role in order to meet market demand, thus it directly influences modularity and integrability and indirectly influences scalability and convertibility.
- Standardization of modules interfaces (SMI), to ensure the interchangeability of modules (Shaik et al., 2014). For Wang et al. (2016), uniform interface standards for the software and hardware of modules are paramount to reduce reconfiguration time and cost. Indeed, the lack of standardization implies spending time and cost in order to adapt and personalise interfaces. Moreover, vendor-independent standards enhance the possibility of using workstations like Lego-bricks (Zuehlke, 2010; Kolberg et al., 2017).
- Components integrating hardware and software elements (CIHS). Their presence improves the integrability of a system. Garetti, Fumagalli and Negri (2015) referred to Cyber Physical Systems (CPSs). They defined CPSs as an evolution of embedded systems based on a tight combination of collaborating computational parts (i.e. micro computing units or embedded systems interconnected by a communication system) that control physical entities. According to the same logic, Scholz et al. (2016) referred to agents. To them, agents are mechanically, computationally and algorithmically distributed robotic modules that are interoperable by definition of mechatronic interfaces. To them, a system composed of agents should enable users to "build a production system out of modules like building with Lego blocks". Kruger and Basson (2016) referred to holons, autonomous and cooperative building block for transforming, transporting, storing or validating information of physical objects.
- Coordination tools (CT) (i.e. management criteria and supporting software). The existence of coordination tools, enabling the coordination of modules, improves integrability. Examples of authors that referred to coordination needs related to modules are Fredriksson (2006), Zhang et al. (2015) and Zuehlke (2010). Fredriksson (2006) referred to three "coordination mechanisms". These are: (i) using pre-defined rules prescribing characteristics and delivery terms of the output of activities or components; (ii) enabling a continuous exchange of information between actors within modules (modules undertake different activities and use

interdependent resources); (iii) using rules directing how activities are undertaken and what resources are used. Reasonably, the first mechanism presupposes the exploitation of planning systems. The second one could benefit from the presence of data and information management models. Finally, the third one presupposes the presence of standardized procedures. To Fredriksson (2006), an example of standardization is a company policy determining the use of certain quality control procedures. In general, coordination tools should be standardized (Kolberg et al., 2017). To Kolberg et al. (2017), currently communication interfaces are tailored to individual needs, implying high efforts for readjustments when facing changes in production processes and IT-Systems. This is not desirable in today's dynamic context.

3.2 Diagnosability

Diagnosability is the ability to identify quickly the sources of quality and reliability problems (Liu et al., 2004). For some authors diagnosability is also the ability to quickly correct operational problems (Koren and Shpitalni, 2010; Gumasta et al., 2011; Singh et al., 2007).

Bruccoleri et al. (2006), decomposed error handling in the following phases: (i) fault detection and identification; (ii) error diagnosis (identify the components which are responsible for the system degradation) and prognosis (identify the future degradation consequences); (iii) error or failure recovery. Depending on how these phases are performed, their durations (and also the associated costs and benefits) change. Thus, supposing unchanged quality of their results, a higher duration would certainly negatively influence diagnosability. Due to the nature of a reconfigurable system – which implies many ramp-up periods along system lifecycle (in order to meet changing market requirements) – the duration of the aforementioned phases is an important parameter. In this regard, Gumasta et al. (2011) decomposed diagnosability in detectability, distinguishability and predictability. To them: (i) "detectability is a measure of the time that passes before the fact that a failure exists and is recognised"; (ii) "distinguishability is a measure of the time required to determine which of a system's line replaceable units is the cause of the loss of functionality; (iii) "predictability is a measure of the time that will pass before a certain failure will occur".

Therefore, the three phases and their durations have been taken as a reference to identify the elements related to diagnosability. To this end, in order to reduce complexity, they have been grouped in two classes of activities: (i) detection and diagnostics and (ii) recovery.

Among the influencing elements, the independent ones are described below.

- Kind of technology exploited for detection and diagnostics (KTDD) (Koren et al. 1999; Mehrabi and Kannatey-Asibu 2001). Wang et al. (2016) proposed a formula to calculate diagnosability that considers the number of diagnosis steps, sample size for diagnosis, and diagnostics accuracy. Again, these aspects depend on the kind of technology exploited for detection and diagnostics.
- Methodology implemented for recovery (MIR) (Bruccoleri et al. 2003; Bruccoleri et al. 2006; Bi et al., 2008). For example, Bi et al. (2008) referred to the use of robots for the automatic calibration of systems and of multi-sensor monitoring systems.

In case of failures or disruptions, system "structure" should allow temporarily changes. Thus, beside the independent elements, there are elements depending on modularity and integrability (see them illustrated in the reminder).

- System adjustability (SA). Adjustability is the ability to modify physically the system (Chaube et al., 2012). For example, Bruccoleri et al. (2003) referred to the possibility to exploit modular components (i.e. components that can be changed and rearranged) in order to positively affect exceptions handling. System adjustability also depends on the technological features of system components.
- Interoperability and intelligence of modules (IIM), that depends on the presence of components integrating hardware and software parts and, in turn, enables the system to implement reactive behaviors in case of disruptions (Scholz et al., 2016; Yan and Vyatkin, 2013; Kruger and Basson, 2016). Thus, this element also impacts on the methodology implemented for recovery. For example, Kruger and Basson (2016), referring to the aforementioned holonic systems, pointed out that they are resilient to disturbances and adaptable in response to faults.
- Presence of redundancies (PR). Muller et al. (2017) observed that, in the event of failure, redundant stations could automatically take over the operations of failed stations. In turn, such a configuration is enabled by the kind of connections between the components of the system (Muller et al., 2017).

Finally, the elements influenced by diagnosability are:

- ramp up time (Koren, 2013), thus responsiveness.
- production quality (Liu et al., 2004), thus productivity.
- reliability (Rosio, 2012), thus productivity.

3.3 Convertibility

For Mehrabi et al. (2000) convertibility allows quick changeover between existing products and quick system adaptability for future products. Farid (2014) proposed a measure of convertibility given by two components: transformation and transportation convertibility. Gumasta et al. (2011) considered the measure of convertibility as the sum of contributions of machines, their arrangements or configuration, and material handling devices.

The elements depending on modularity and integrability and influencing convertibility are illustrated in the reminder.

- System adjustability (SA) (Maier-Speredelozzi et al., 2003; Elmaraghy, 2006; Rosio, 2011; Puik et al., 2017; Gu et al. 2004). In turn, system adjustability depends also on mobility of system components (Elmaraghy, 2006; Rosio, 2011). Puik et al. (2017) explained that reconfigurability implies the presence of modules that could be either repeated, or adapted (then converted), or expanded (then scaled) in order to reconfigure the system. Moreover, many authors referred the kind of transportation devices as componet affecting system convertibility (Carpanzano et al. 2016; Elmaraghy, 2006; Scholz-Reiter et al. 2015). For example, Maier-Speredelozzi et al. (2003) referred to “material handling connections” impacting on convertibility.

- Managerial practices (MP). Reasonably, these practices depend on coordination tools (i.e. management criteria and supporting software) exploited. Indeed, Elmaraghy (2006) mentioned soft aspects of system conversions, such as the activities of re-programming, re-routing, re-planning, re-scheduling. Abdi and Labib (2017) also provided examples of practices, mentioning machine relocation, conveyor redirections and labour reassignment. Reasonably, these activities depend on the kind of managerial practices used to manage the system.

- Use of equipment and techniques to reduce time and cost of conversion (ETRTCCV). Indeed, these equipment and techniques ensure that adjusting the functionality of the system allows responding rapidly to market demands and fulfil productivity (Abbassi and Housmand, 2011). However, the reduction of costs and time of reconfiguration can be achieved only if interfaces and procedures are standardized (Wang et al., 2016; Kolberg et al., 2017).

- Incrementality of changes (IC). A system that is reconfigured through small conversions possesses higher convertibility (Maier-Speredelozzi et al. 2003; Hees and Reinhart 2015).

Finally, the element depending on diagnosability and influencing convertibility is:

- the use of equipment and techniques to reduce system ramp-up time (ETRRT). Converting an existing system to cope with changing demand requires many ramp-up periods along system lifecycle. Thus, the reduction of system ramp-up time, achieved through diagnosability, allows more frequent reconfigurations.

3.4 Scalability

Scalability is the counterpart characteristic of convertibility (Koren, 2006). According to the aim of this paper, elements influencing and influenced by scalability and convertibility are overlapped.

The elements depending on modularity and integrability and influencing scalability are illustrated in the reminder.

- System adjustability (SA) (Maier-Speredelozzi et al., 2003; Elmaraghy, 2006; Rosio, 2011; Puik et al. 2017; Gu et al., 2004; Chaube et al., 2012). According to Farid and McFarlane (2006), the continual introduction of new product families and their associated variants requires flexible adjustments of the capacity by adding new production and material handling resources and/or their tooling. Further authors noticed that the kind of transportation system also affects scalability (Elmaraghy, 2006; Scholz-Reiter et al., 2015).

- Managerial practices (MP). Reasonably, these practices depend on coordination tools (i.e. management criteria and supporting software) exploited. Indeed, ElMaraghy (2006) mentioned soft aspects of system capacity changes, such as the activities of sub-contracting, utilization of shifts (time) and operators (human resources). These activities depend on the kind of managerial practices used to manage the system.

- Use of equipment and techniques to reduce time and cost of capacity change (ETRTCCC). Indeed, these equipment and techniques ensure that adjusting scalable production capacity of the system allows responding rapidly to market demands and fulfil productivity (Abbasi & Houshmand, 2011). However, the reduction of costs and time of reconfiguration can be achieved only if interfaces and procedures are standardized (Wang et al., 2016; Kolberg et al., 2017).

- Incrementality of changes (IC). A system that can be adjusted to meet a new market demand by adding a small incremental capacity is highly scalable (Koren et al., 2016; Wang et al., 2016; Hees and Reinhart, 2015).

Finally, as observed for convertibility, the element depending on diagnosability and influencing scalability is:

- the use of equipment and techniques to reduce system ramp-up time (ETRRT). Koren (2013) observed that scalability and diagnosability complement to each other because scaling-up of an existing system to cope with changing demand requires a subsequent ramp-up period that can be reduced dramatically by implementing the diagnosability characteristic.

3.5 Customization

Reconfigurable systems are built around product families and their configuration evolves in response to changes in the product functionality and capacity (Goyal et al., 2013). According to the definition of customization itself, there are independent elements influencing customization. These are:

- market changes (MC);

- market driven approach (MDA). In order to be customized, system reconfigurations should be driven by market requirements.

According to Wang et al. (2016), in terms of functionality, customization determines high utilization rate for the subsystems.

Regarding the dependent elements, the joint action of scalability and convertibility enables system customization. Shabaka and ElMaraghy (2007) wrote that customization is realized by, for example, adding/removing modules, changing system layout, or integrating new process monitoring technology. Achieving customization requires more conversions and changes of production capacity along system lifecycle, in order to meet new market requirements.

Finally, the elements influenced by customization are reported below.

- Responsiveness (Abbassi and Housmand, 2011; Abdi & Labib 2003).
- Productivity (Wang et al., 2016; Abbassi and Housmand, 2011).

4. CONCLUSIONS

In this paper, the elements influencing the core characteristics of reconfigurability have been identified and gathered in a comprehensive framework that also takes into account the existing relationships between characteristics. To this end, the available literature has been exploited.

This research is considered a first step to understand how manufacturing firms can achieve reconfigurability. Indeed, it is considered a preparatory step in order to encourage the construction of quantitative indicators of the six core characteristics that take into account also the relationships between such characteristics. To this end, the framework is based on references proposing quantitative measures of reconfigurability. The quantification of the elements of the framework will allow manufacturing firms identifying benefits of reconfigurability (in terms of responsiveness and extension of system lifecycle) and to compare them with the costs incurred to invest in reconfigurable manufacturing systems. The benefits depend on the elements influenced by diagnosability and customization. Instead, the investment costs depend on the independent influencing elements impacting on modularity, integrability and diagnosability. Therefore, further research should be performed in order to find quantitative indicators incorporating the highlighted elements. To do so, the implementation of case studies and the collection of opinion of experts operating in manufacturing firms could help building the quantitative measures. Reasonably, for a complete assessment of reconfigurability, also qualitative aspects should be taken into account involving the challenge of opportunely quantify them.

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