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Reconfigurable Manufacturing: A Classification of Elements enabling Convertibility and Scalability

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Abstract. Reconfigurable manufacturing, providing capacity and functionality on demand, is an ever more important factor of competitiveness in volatile, unpre-dictable, and rapidly changing markets. In this regard, scalability and convertibil-ity are considered particularly relevant characteristics, as they directly reduce re-configuration effort and enhance system responsiveness. However, in previous research, scalability and convertibility have predominately been addressed con-ceptually on a high level of abstraction with only limited consideration of how specific manufacturing elements can enhance and realize them. Therefore, the ob-jective of this paper is first to identify and classify elements enabling scalability and convertibility in order to bring reconfigurability-related concepts closer to the world of practitioners. Moreover, as a result, the paper concretizes scalability and convertibility and provides a foundation for future empirical research on recon-figurability.

Keywords: Reconfigurable Manufacturing, Reconfigurability, Changeable Man-ufacturing, Scalability, Convertibility.

1 Introduction

Reconfigurability of manufacturing systems has been studied since the late 90's as a key to competitiveness in scenarios characterized by unpredictability of markets [1]. In addition, emerging intelligent manufacturing technologies promise to enable and enhance reconfigurability [1], [2]. However, despite these promising potentials, the wide implementation of manufacturing solutions realizing the reconfigurability char-acteristics still appears rather limited in industry [2], [3]. It is widely recognized that the core characteristics of reconfigurability are: modularity, integrability, diagnosabil-ity, scalability, convertibility and customization. Among them, scalability and con-vertibility are considered essential characteristics [4], [5]. Scalability, i.e. the ability to make rapid and efficient incremental changes of capacity [6], and convertibility, i.e. the ability to conduct quick changeover between existing products and adaptability to future products [7], represent key reconfigurability characteristics, as they directly contribute to the goal of the reconfigurable systems, which is providing exactly the capacity and functionality needed when needed [8]. Moreover, scalability and con-vertibility directly reduce reconfiguration effort and enhance system responsiveness [9], [10], as well as "bridge" between the remaining characteristics since they are ena-bled by modularity, integrability and diagnosability and, in turn, enable customiza-tion and thus reconfigurability itself [11], [12].

Therefore, in this paper, scalability and convertibility are considered as primary characteristics in order to realize the advantages of reconfigurability in manufactur-ing firms. However, in previous research, these characteristics have predominately been addressed on rather abstract levels with only limited consideration of the manu-facturing elements that enhance these characteristics, their inherent relations, and how they can actually be realized in manufacturing [13]–[15]. In this regard, recon-figurability is increasingly being promoted as a multi-dimensional and complex ca-pability that can be designed and implemented specifically for different manufactur-ing contexts, by exploiting relationships between core characteristics and/or enablers [13], [14] at multiple manufacturing levels [16], [17]. Therefore, in order to support practitioners in realizing the potentials of reconfigurability and design appropriate manufacturing solutions that realize reconfigurability, it is important to consider not only structural aspects that enable scalability and convertibility but also their manu-facturing levels of realization. Accordingly, the aim of this paper is to bring reconfigu-rability-related concepts closer to the world of practitioners and create the foundation for future field-based investigations on the topic, leading to the following research question: Which manufacturing elements enable scalability and convertibility as relevant characteristics of reconfigurability in manufacturing?

In addressing this research question, "elements" enabling scalability and converti-bility are defined as concrete constituents of such characteristics. Moreover, focus is limited to the factory and lower manufacturing levels, where previous research on manufacturing "elements", "enablers" or "assessment criteria" (enabling specific characteristics of reconfigurability and/or enabling reconfigurability as a capability in itself [3], [18]–[20]) has been considered. For this purpose, criteria have been defined for analyzing previous research and ensure coverage of reconfigurability as a multi-dimensional capability and in turn create a basis for future research based on case studies. The remainder of the paper is structured as follows: Section 2 presents criteria for identifying and classifying enabling elements, Section 3 provides the results and Section 4 presents conclusions and outlines future development of this research.

2 Classification Criteria for Elements Enabling Scalability and Convertibility

This section presents the criteria applied for classification of different elements identi-fied in previous research. These have been introduced in order to cover relevant as-pects related to scalability and convertibility from a multi-dimensional perspective. The criteria are described as follows:

- Manufacturing level of reference: from a hierarchical systems view, reconfigu-rability can be developed on different manufacturing levels [21]. Moreover, recon-figurability on lower manufacturing levels positively influences reconfigurability on higher manufacturing levels [16], [22], [23]. Thus, elements influencing scalabil-ity and convertibility should be identified in regard to multiple levels. Specifically, this paper focuses on levels within the factory: (i) workstation (WL), (ii) system (SL), and (iii) factory (FL).
- Effects on either short-term or long-term reconfigurations: as a multi-dimensional capability, reconfigurability has characteristics acting in the Configu-ration Period (CP) and others acting in the Reconfiguration Period (RP) [11]. CP is the period for decisions on structural aspects (i.e. the design) of systems, whereas RP is the period for decisions on system changes (i.e. related to the operations). Scalability and convertibility are characteristics acting during the RP [11], thus their enabling elements support reconfigurations with either short or long-term time horizon. Short-term time horizon reconfigurations (ST) cover e.g. solving disrup-tions and quality problems, exploiting flexible production resources or changing from one existing variant to another (i.e. changes within workstations, leading to brief changeovers without any further investment in production resources) [24]. Long-term time horizon reconfigurations (LT) are associated with changes of structural aspects at either workstation, system and factory levels, in order to change production capacity and functionality [25].
- Classification in physical and managerial elements: depending on manufactur-ing levels, the nature of elements influencing scalability and convertibility may be different. As observed by many authors, reconfigurability at lower levels is general-ly associated with physical and "hard" elements, while reconfigurability on higher levels is generally associated with more managerial, logical, and "soft" elements [6], [10], [16], [21]. Physical elements (PE) can be either technical systems of the factory (i.e. operational resources and processes) and spatial aspects (i.e. floor and ground areas) [17]. Managerial elements (ME) refer to logical elements, operation-al rules, organizational policies, and IT support for the management of technical systems [10], [17], e.g.

rules established for re-planning production resources in or-der to accomplish market changes [6].

In the following, nine elements have been identified and classified according to these criteria. In this regard, relevant literature was located from authors' previous system-atic literature searches on reconfigurability, which collectively have used a broad spectrum of key words e.g. "reconfigurability", "reconfigurable manufacturing sys-tem", "changeable manufacturing", etc. in relevant databases e.g. Web of Science and Scopus, as well as through additional snow-ball search processes. Papers referring to: (i) "changeability", often used to denote to the capability of manufacturing sys-tems to adapt to any changes independently on the manufacturing level of reference [4], [26]; (ii) "flexibility", often used at workstation and system levels [6]; and (iii) "transformability" often used at factory level [3], [4] have been reviewed as well.

3 Research Results: Elements Enabling Scalability and Convertibility

This section presents the elements enabling scalability and convertibility identified in the literature review. Fig. 1 synthesizes the classification of these elements accord-ing to the aforementioned criteria through the color-coded labels visualized for each element. The figure shows that scalability and convertibility are enabled by a combi-nation of nine manufacturing elements, which are comparatively less abstract than scalability and convertibility. These nine elements are enabled by a combination of other aspects that are, in turn, more concrete than the previous ones. For brevity, these have not been included in detail here. Even if not detailed, such aspects have been immersed and exemplified in the following description of the nine elements. As observable in the following descriptions of the nine elements, elements and aspects are positioned in Fig.1 progressively enlarging, from left to right, the focus from WL, to SL and then to the entire FL.

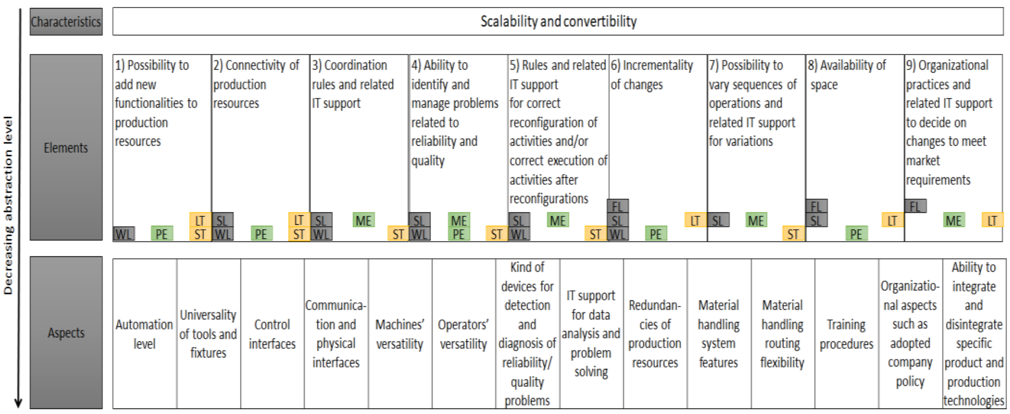

Fig. 1. Elements enabling scalability and convertibility and their classifications.

1) Possibility to add new functionalities to production resources: this element has been located at WL and classified as PE. Indeed, operators and machines should be provided or designed (in case of machines) in a way that allows future conversions to new requirements. Specifically, manual workstations rely on operators' versatile skills [7], [17]. Conversely, to facilitate future conversions of highly automated work-stations with complex and partitioned architectures, machines' control interfaces should be designed for easy integration to newly introduced tools/machines [13]. Universality of tools and fixtures adopted at the workstation would facilitate their employment for varying requirements and tasks [13]. In general, the possibility to add new functionalities to production resources may allow ST scalability and con-vertibility (e.g. by recurring to operators' versatility) or even LT reconfigurations (e.g. exploiting machines interfaces allowing integration to newly introduced tools/machines).

2) Connectivity of production resources: this element has been classified as PE and defined at WL and SL. Indeed, as it allows information exchanges, from the perspective of supporting information systems, it should be defined and supported at every individual manufacturing level [27]. Information may simplify the adaption of operators and/or machines to eventual new requirements in terms of implemented functionalities [20], [28]. Connectivity may certainly simplify ST reconfigurations (e.g. interactive screens and information boards connected to a central information system might guide operators in executing a certain variety of tasks [29]); conversely LT reconfigurations should be enabled by additional aspects allowing structural changes of the workstation (e.g. the integrability of machines interfaces).

3) Coordination rules and related IT support [19]: these elements may be defined at both WL and SL. Rules are ME even if the possibility to benefit of the IT support is also related to the connectivity of production resources. Both rules and IT support are enablers of scalability and convertibility only if, during the CP, these are designed with a RP perspective: in this case, they would be oriented at speeding up the adaptation to change by improving production resources synchronization during reconfigu-rations, thus allowing more frequent reconfigurations [30], [31].

4) Ability to identify and manage problems related to reliability and/or to produc-tion quality: this element may be defined at both WL and SL. It includes both PE, such as devices for detection and diagnosis of reliability/quality-related problems [18], [20], and ME such as problem-solving methodologies and related IT support [32]. PE should be defined especially at WL and ME should be defined (and support-ed by adequate information systems) especially at SL. Moreover, the exploitation of modern digital technologies promise to improve such ability [2], [33]. It enables better scalability and convertibility at WL and SL by allowing the reduction of ramp-up periods after reconfiguration [30].

5) Rules and related IT support ensuring the correct reconfiguration of produc-tion/assembly activities and/or the correct execution of activities after reconfigura-tions: these elements may be defined at both WL and SL. These are ME, even if the possibility to benefit of the IT support also presupposes the presence of PE. Both rules and IT support are enablers of scalability and convertibility only if, during the CP, these are designed with a RP perspective. In this case, they would be oriented at avoiding problems related to human mistakes during reconfigurations and/or after reconfigurations, thus allowing more frequent reconfigurations by contributing to the reduction of reconfiguration ramp-up times [30]. At WL these might be mechanisms to detect the usage of right tool and right components for a certain task (poka yoke) [20].

6) Incrementality of changes: at each level (i.e. WL, SL and FL) converting and/or adapting production capacity through as small as possible changes means higher convertibility and/or scalability [34]. Intuitively, the incrementality of changes achieved at WL, strongly influences the incrementality of changes at SL and in turn at FL. As detailed below, many aspects of this element should be properly designed during the CP, these may enable, especially at higher manufacturing levels, LT scala-bility and convertibility by reducing the effort required for reconfigurations [34]. At WL, an influencing aspect is the versatility of operators and integrability of ma-chines' control interfaces, which favor implementing incremental changes of work-stations without implying substantial changes of workstations themselves [13]. At SL, the universality of workstations may allow accomplishing incremental changes, for example the possibility to share and or swap functional units among stations. [3], [18], [20]. Moreover, features of the material handling system, such as the level of automation of its devices and the possible movements of these systems, impact on the incrementality of changes too [20]. At FL, incrementality of changes can be seen as technical "upgradeability" of the factory [2]. It depends on the ability to integrate and disintegrate specific product and production technologies [17]. Finally, by analo-gy with SL, the level of automation of warehouse systems may affect factory recon-figurability. Thus, generally this element supports LT reconfigurations.

7) Possibility to vary sequences of operations and related IT support: this element may be defined at SL as a ME, however it also depends on PE, such as the presence of functional redundancies of workstations/

functional units [19] and specific fea-tures of the material handling system [6], [20]. Examples related to this element are opportunities and decisions on machines relocation [35] and material handling redi-rections [35]. Even in this case, the possibility to benefit of the IT support is related to the connectivity of production resources at WL. It enables ST scalability and convert-ibility. Indeed, the number of feasible routes of all part types and the availability of this information for decisions on system operational changes positively impacts on changes in production capacity and functionality [6]. In turn, this aspect depends on the versatility of operators' skills and/or the integrability of machines' control inter-faces [20].

8) Availability of space (this is mainly influencing scalability rather than converti-bility): the utilization of space at SL and FL potentially allows increasing the number of resources in case of need [20]. Thus, this element enables LT reconfigurations.

9) Organizational practices and related IT support to decide on changes on the op-erations to meet market requirements: such ME at FL enables LT reconfigurations. These are: labor reassignment [35] and training procedures (such as cross training and continuous improvement of operators skills; outsourcing and subcontracting possibili-ties [6]; exploitation of different processing plans available for making a product [7]; possibility to act on shifts and flexible labor time [7]. For example, the possibility to change shifts and number of resources involved [6], [20] is a ME that has to be de-fined at FL during the CP and, once defined, it allows implementing LT-oriented changes of production capacity and functionality at either WL and SL. It should depend on organizational aspects such as adopted company policy.

4 Conclusions and Further Research

The aim of the research presented in this paper was to bring reconfigurability-related concepts closer to the world of practitioners. Accordingly, nine manufacturing ele-ments enabling scalability and convertibility have been identified from previous re-search and classified according to criteria defined with the aim of exploring the multi-dimensional aspects of reconfigurability, i.e. manufacturing level, time-span of re-configuration effect, and as being either managerial or physical. These nine elements contribute with a concretization of abstract concepts of scalability and convertibility and bring these reconfigurability-concepts closer to practice. Future research should aim at further enhancing the theoretical classification through feedback and exam-ples gathered directly in field. Moreover, cases should allow understanding how such elements can increase convertibility and scalability. Specifically, since empirically-founded or case-based research on reconfigurability is rather scarce, future research should aim at investigating e.g. elements of scalability and convertibility in practice in regard to their inherent relations, reinforcing effects, different types of applications, and resulting performance outcomes.

References

1. Koren, Y., Gu, X. Guo, W.: Reconfigurable manufacturing systems: Principles, design, and future trends. Front. Mech. Eng., 13(2), 121–136 (2018).

2. Maganha, I., Silva, C., Ferreira, L. M. D. F.: Understanding reconfigurability of manufactur-ing systems: An empirical analysis. J. Manuf. Syst 48, 120–130 (2018).

3. Andersen, A.-L., Larsen, J. K., Brunoe, T. D., Nielsen, K., Ketelsen, C.: Critical enablers of changeable and reconfigurable manufacturing and their industrial implementation. J. Manuf. Technol 29(6), 983–1002 (2018).

4. Wiendahl, H. P., ElMaraghy, H. A., Nyhuis, P., Zah, M. F., Wiendahl, H. H., Duffie, N., Brieke, M.: Changeable Manufacturing - Classification, Design and Operation. CIRP Ann. - Manuf. Technol., 56(2), 783–809 (2007).

5. Rösiö, C.: Supporting the design of reconfigurable production systems. Mälardalen Univer-sity Press PhD Dissertations, (2012).

6. Elmaraghy, H. A.: Flexible and reconfigurable manufacturing systems paradigms. Int. J. Flex. Manuf. Syst 17, 261–276 (2006).

7. Mehrabi, M. G., Ulsoy, A. G., Koren, Y.: Reconfigurable manufacturing systems and their enabling technologies. International Journal of Manufacturing Technology and Management, 1(1): 1–21 (2000).

8. Koren, Y.: General RMS Characteristics. Comparison with Dedicated and Flexible Systems. Chapter 3 in Reconfigurable Manufacturing Systems and Transformable Factories, pp. 27–44. Springer, Berlin, Heidelberg (2006).

9. Elmaraghy, H. A.: Reconfigurable process plans for responsive manufacturing systems. In Digital Enterprise Technology, pp. 35–44. Springer (2007).

10. Ayman, M., Youssef, A., ElMaraghy, H. A.: Assessment of manufacturing systems recon-figuration smoothness. Int. J. Adv. Manuf. Technol., 30(1–2), 174–193 (2006).

11. Napoleone, A., Pozzetti,A., Macchi, M.: A framework to manage reconfigurability in manu-facturing. Int. J. Prod. Res., 56 (11), 3815-3837 (2018).

12. Singh, A., Gupta, S., Asjad, M., Gupta, P.: Reconfigurable manufacturing systems: journey and the road ahead. Int. J. Syst. Assur. Eng. Manag. 8(s2), 1849–1857 (2017).

13. Hawer, S., Braun, N., Reinhart,G.: Analyzing Interdependencies between Factory Change Enablers applying Fuzzy Cognitive Maps. In: Procedia CIRP, vol. 52, pp. 151–156 (2016).

14. Andersen, A.-L., Nielsen, K., Brunoe, T. D.: Understanding Changeability Enablers and Their Impact on Performance in Manufacturing Companies. In: IFIP International Confer-ence on Advances in Production Management Systems, vol. 536, pp. 297–304 (2018).

15. Russo Spena, P., Holzner, P., Rauch, E., Vidoni, R., Matt, D. T.: Requirements for the De-sign of flexible and changeable Manufacturing and Assembly Systems : a SME-survey. In Procedia CIRP, vol. 41, pp. 207–212 (2016).

16. Andersen, A.-L., Brunoe, T. D., Nielsen, K.: Reconfigurable Manufacturing on Multiple Levels: Literature Review and Research Directions. In: IFIP International Conference on Advances in Production Management Systems, pp. 266–273 (2015).

17. Nyhuis, P., Heinen, Æ. T., Brieke, Æ. M.: Adequate and economic factory transformability and the effects on logistical performance. International Journal of Flexible Manufacturing Systems, 19(39), 286–307 (2007).

18. Beauville, A., Klement, N., Gibaru, O., Roucoules, L., Durville, L.: Identification of recon-figurability enablers and weighting of reconfigurability characteristics based on a case study. In: Procedia Manufacturing, vol. 28, pp. 96-101 (2019).

19. Napoleone, A., Pozzetti, A. Macchi, M.: Core Characteristics of Reconfigurability and their Influencing Elements. In: IFAC-PapersOnLine, vol. 51, no. 11, pp. 116–121 (2018).

20. Rösiö, C., Aslam, T., Banavara, K., Shetty, S.: Towards an assessment criterion of reconfig-urable manufacturing systems within the automotive industry. In: Procedia Manufacturing, vol. 28, pp. 76-82 (2019).

21. Bi, Z. M., Lang, S. Y. T., Shen, W., Wang, L.: Reconfigurable manufacturing systems: the state of the art. Int. J. Prod. Res, 46(4), 967–992 (2008).

22. Bruccoleri, M., Lo Nigro, G., Perrone, G., Renna, P., Noto La Diega, S.: Production plan-ning in reconfigurable enterprises and reconfigurable production systems. CIRP Ann. - Manuf. Technol., 54(2), 433–436 (2005).

23. Goyal, K. K., Jain, P. K. K., Jain, M.: Optimal configuration selection for reconfigurable manufacturing system using NSGA II and TOPSIS. Int. J. Prod. Res., 50(15), 4175–4191 (2012).

24. Bruccoleri, M., Amico, M., Perrone, G.: Distributed intelligent control of exceptions in re-configurable manufacturing systems, International Journal of Production Research, 41(7), 1393–1412 (2003).

25. Koren, Y. Gu, X., Guo, W.: Choosing the system configuration for high-volume manufac-turing. Int. J. Prod. Res., 56(1-2), 476-490 (2017).

26. Terkaj, W., Tolio, T., Valente, A.: A review on manufacturing flexibility. International Jour-nal of Production Research, 51(19), 41–61 (2009).

27. BSI-Standards: IEC62264 Enterprise-control system integration (2013).

28. Otto, J., Vogel-Heuser, B., Niggemann, O.: Automatic Parameter Estimation for Reusable Software Components of Modular and Reconfigurable Cyber-Physical Production Systems in the Domain of Discrete Manufacturing. In: IEEE Trans. Ind. Informatics, vol. 14, no. 1, pp. 275–282 (2018).

29. Posada, J., Toro, C., Barandiaran, I., Oyarzun, D., Stricker, D., Amicis, R., Pinto, E., Eisert, P., Döllner, J., Vallarino, I.: Visual Computing as Key Enabling Technology for In-dustry 4.0 & Industrial Internet. In: IEEE Comput. Graph. Appl., vol. 35, no. 2, pp. 26–40, (2015).

30. Koren, Y.: The rapid responsiveness of RMS. Int. J. Prod. Res, 51(23–24), 6817–6827 (2013).

31. Cheng, Y., Zhang, Y., Ji, P., Xu, W., Zhou, Z., Tao, F.: Cyber-physical integration for mov-ing digital factories forward towards smart manufacturing: a survey. Int. J. Adv. Manuf. Technol., 97, 1209–1221 (2018).

32. Bruccoleri, M., Pasek, Z. J., Koren, Y.: Operation management in reconfigurable manufac-turing systems: Reconfiguration for error handling. Int. J. Prod. Econ., 100(1), 87–100 (2006).

33. Bortolini, M., Galizia, F. G., Mora, C.: Reconfigurable manufacturing systems: Literature review and research trend. J. Manuf. Syst., 49, 93–106 (2018).

34. Koren, Y., Wang, W., Gu, X.: Value creation through design for scalability of reconfigura-ble manufacturing systems. Int. J. Prod. Res., 55(5), 1227–1242 (2016).

35. Abdi M. R., Labib, A.: RMS capacity utilisation: product family and supply chain. Int. J. Prod. Res, 55(7), 1930–1956 (2017).