A Tool for the Comparison of Concept Designs of Reconfigurable Manufacturing Systems

Napoleone, Alessia; Brunø, Thomas Ditlev; Andersen, Ann-Louise; Nielsen, Kjeld

Published in:
Procedia CIRP

DOI (link to publication from Publisher):
10.1016/j.procir.2021.11.189

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 104 (2021) 1125–1130

www.elsevier.com/locate/procedia

54th CIRP Conference on Manufacturing Systems

A Tool for the Comparison of Concept Designs of Reconfigurable Manufacturing Systems

Alessia Napoleone[a,*], Thomas Ditlev Brunoe[a], Ann-Louise Andersen[a], Kjeld Nielsen[a]

[a]*Department of Materials and Production, Aalborg University, Fibigerstræde 16, Aalborg 9220, Denmark*

* Corresponding author. Tel.: +45-2256-9484. *E-mail address:* alna@mp.aau.dk

Abstract

Reconfigurable Manufacturing Systems (RMS) deserve the interest of both academics and practitioners, as they allow manufacturing companies to deal with unpredictable market requirements, which is increasingly important. Moreover, the availability of Industry 4.0 technologies promises to support RMS and turn them into Cyber-Physical Systems. However, practitioners still need guidance and tools to design and build RMS. To pursue any investment strategy in these systems, companies need to be adequately aware of RMS' benefits, since the initial stage of RMS design. To this end, this research focuses on the evaluation of concept designs of RMS, which should precede the investment in the detailed design and be sufficiently comprehensive on one hand, and as practical as possible to engage practitioners on the other hand. For this reason, a tool combining Analytical Hierarchical Process (AHP) and Pugh Matrix methods is proposed for fast and effective comparison of concept designs of RMS. Being part of an industry project, the tool has been validated in an actual context of development of RMS concept designs.

Keywords: Reconfigurable Manufacturing System (RMS); Design criteria; Design methodology; Analytical Hierarchical Process (AHP); Pugh Matrix.

1. Introduction

Unpredictable market requirements, shorter product lifecycles, and demand for customized products lead manufacturing companies to seek responsiveness and cost-effectiveness to achieve competitiveness [1]. To this end, companies should implement Reconfigurable Manufacturing Systems (RMS), which capacity and functionality can be modified exactly when required, while reducing time and costs of a system's reconfiguration [2].

Despite the great potential of RMS, their concrete implementation in manufacturing companies is still far from becoming reality [3]. Both research and practice suggest the need for practical and company-specific guidelines driving practitioners in the transition toward the RMS paradigm (as summarized in [4,5]). Indeed, companies need practical tools to support the design of RMS [6,7]. The design of any manufacturing systems covers different stages: from the long-term justification of the investment, to the detailed design, including physical building and ramp-up of the system. The most difficult stage in RMS design is the long-term justification of the investment because practitioners should adopt a system lifecycle perspective and consider the uncertain nature of many variables [4]. Indeed, unlike traditional systems, over its lifecycle, an RMS goes through configuration periods (in which it is configured to produce a specific product family, required for a specific period) and reconfiguration periods (in which the system undergoes modifications to allow the production of a new product family) [8]. Moreover, the initial stage of RMS design is supposed to involve and engage multiple stakeholders within the company (such as business and operational managers), which is an extremely relevant requirement for the successful implementation of the whole design project [9,10]. Obtaining the engagement of

10.1016/j.procir.2021.11.189

stakeholders is even more critical considering that today many companies are not yet aware of RMS and their potentialities [11]. Finally, the selection of the best concept with which to proceed to detailed design is one of the most difficult, sensitive and critical problems in RMS design [12].

This study aims to provide a practical tool to support the initial stage of RMS design. Specifically, two research questions (RQ) are addressed:

RQ1. "what general criteria drive RMS design and how should they be introduced to manufacturing companies to engage relevant stakeholders into the design of RMS?"

RQ2. "what practical tool for the comparison of concept designs of RMS can be provided to manufacturing companies?"

The following section 2 presents the research methodology of this study, section 3 and 4 respectively answer to the RQ1 and RQ2. Finally, section 5 presents conclusions and outlines future development of this research.

2. Research methodology

The RQ1 aims to provide general guidelines to practitioners (i.e., not company-specific), so to allow any company from any manufacturing sector to value the design of RMS against traditional systems. On the other hand, the RQ2 aims to provide a practical and company-specific tool to compare concept designs of RMS with each other and/or with traditional systems.

Addressing the RQ1 consists in the identification of general criteria driving RMS design and of an appropriate way to represent them to companies. Specifically, being at the initial stage of the design, a multitude of different criteria needs to be considered and understood, this might be challenging for practitioners, yet essential for their engagement into the design of RMS. To simplify practitioners' understanding, in this study the criteria have not been just listed down but have been represented in a hierarchy which shows their relationships. Moreover, when addressing the RQ2, the Analytical Hierarchical Process (AHP) has been selected for comparison of RMS concept designs, and the implementation of this method requires the preliminary definition of a hierarchy of decision-making criteria. In other words, the hierarchy of criteria is an input for the tool to compare concept designs of RMS. The overall research process is represented in the following figure (Fig. 1).

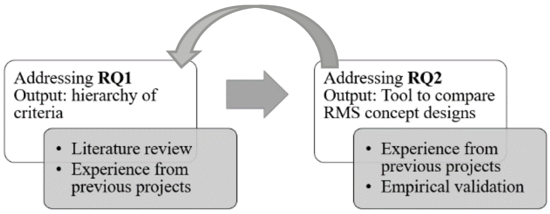


Fig. 1. Research Process

To have an initial grounded reference for the hierarchy proposed to answer to the RQ1, knowledge from both literature and authors' previous experience in projects with companies has been exploited.

To this end, literature on the use of the AHP method for RMS has been reviewed. Moreover, in RMS literature the AHP method has often been adopted. The authors conducted a structured literature review [13] and, using Scopus as search database, identified 31 documents by combining the keywords AHP (or Analytical Hierarchical Process), and RMS (or Reconfigurable Manufacturing System). Among the 31 identified documents, two referred to the same study and four were excluded for being out of scope. The remaining 26 documents were carefully analysed and categorised in two different classes: (i) 15 out of 26 implemented the AHP for design aspects of RMS (ii) the other 11 implemented it for operational aspects (such as performance evaluation [14–16]) of RMS. Within the 15 studies on design aspects, five focused on the initial stage of RMS design and thus are the main reference for the hierarchy proposed in this study [17–21]. Furthermore, as detailed in section 3, to ensure the inclusion of all relevant criteria along system lifecycle, the proposed hierarchy also includes criteria derived from the remaining documents of the sample (studies focused on either the detailed design or on operational aspects of RMS).

To ensure both the engagement of practitioners and the understandability of criteria, the hierarchy was adjusted based on previous projects with companies. Specifically, the authors previously supported specific companies in evaluating investments in RMS (to this regard, see [22]). Experience with practitioners strengthened the need to refer to an adequately broad set of criteria, because companies differ from each other, thus they have company-specific goals. In addition, reconfigurability has a multidimensional nature [22], meaning that even in the same company, concept designs of RMS can be very different from each other and practitioners are asked to compare and choose among them based on the most relevant criteria to them. To make these evaluations, practitioners need to perfectly understand the criteria. Therefore, as detailed in section 3, experience with companies led the authors to seek for the exhaustiveness and clarity of the criteria of the proposed hierarchy.

As for results, tackling the RQ1 has led to the identification of a general hierarchy, described in section 3.

Addressing the RQ2 consists in the identification of a practical tool for the comparison of concept designs of RMS. The identification and definition of the tool has been driven by experience from previous projects with companies. Furthermore, this research is part of an industry project and the tool has been validated in the context of an actual development project of RMS concept designs. The tool is described in section 4.

3. A general hierarchy for manufacturing companies

The proposed hierarchy has five levels. The first two levels are represented in the following figure (Fig. 2).

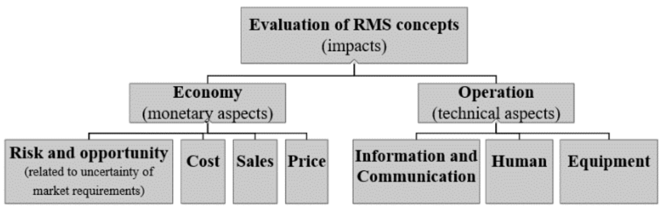


Fig. 2. Levels 1 and 2 of the proposed hierarchy

As shown in Fig. 2, both economy (i.e. monetary aspects, such as cost and sales) and operation (technical aspects, including manufacturing equipment, human resources and information and communication) criteria should be considered [17,19,23]. As done by Abdi and Labib [18], under the economy criterion, the risk related to uncertainty of market requirements has been included. In this proposal, to engage practitioners and make them aware of the benefits of RMS against traditional systems, such criterion is slightly more self-explanatory by mentioning the "opportunity" associated to the aforementioned "risk": the modular nature of an RMS ideally makes it adaptable to unexpected requirements with an adequately low effort. As remarked by Rehman and Babu [24], the evaluation of concept designs of systems under different scenarios allows to reap the potential benefit of RMS. Thus, the "risk and opportunity" item stimulates practitioners to adopt a system lifecycle perspective.

Among the economy criteria, only cost has criteria at lower levels. At level 3, these are capital and operational expenses. In this proposal, unlike previous literature [18,19,21], the capital expenses have been explicitly divided into two components: the expenses related to the initial investment and those incurring after reconfigurations as shown in the following figure (Fig. 3).

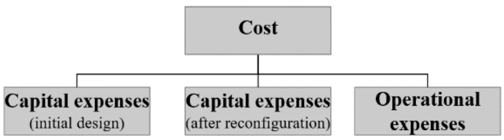


Fig. 3. Level 3 – Specification of costs

This additional distinction aims to support practitioners' adoption of a lifecycle perspective to actually identify the benefits of RMS. Under the three components of cost shown in Fig. 3, many cost items are listed. These are:

- economic and environmental sustainability (see [25]). As remarked by Battaïa et al [26], the optimal use of resources over system lifecycle, which is the base of the RMS concept, substantially reduces the economic and environmental impact of such systems
- design and test of the manufacturing system (incurred before producing the actual solution)
- production and ramp-up of the manufacturing system (incurred for the production of the actual solution)
- buildings/ space occupation
- manpower (e.g. see [19])
- materials and components (also including end-products transportation) (e.g. see [19])
- maintenance (e.g. see [19])
- transportation/ mobility (of equipment's modules)
- quality of end products (e.g. see [17])
- safety of end products
- safety of the work environment

Asking practitioners to evaluate the aforementioned costs distinguishing between their components in terms of (i) initial design capital expenses, (ii) capital expenses after reconfiguration, and (iii) operational expenses, further stimulates the adoption of a lifecycle perspective.

On the operational side, each item at Level 2 of Fig. 2 has lower levels.

Regarding the human criterion, it can be decomposed in:

- skills required to either operators and/or engineers to operate and reconfigure the new manufacturing system [17,27], and
- organisational changes, in terms of new roles/responsibilities led by the introduction of the new system and/or temporary needs to acquire specific skills during system ramp-ups (based on Abdi and Labib [18] and experience from previous projects with companies).

Today, the information and communication criterion shown in Fig. 2 is even more relevant because new "Industry 4.0" technologies promise to support RMS and turn them into Cyber-Physical Systems [2,28]. To ensure that these technologies support companies in achieving their goals, their design needs to be part of the manufacturing system design [29]. Thus, to remark this aspect, in this proposal the lower levels of the information and communication criterion are:

- new requirements in terms of data and information led by the introduction of the new system
- new requirements in terms of planning systems led by the introduction of the new system

Therefore, these new requirements should be considered when designing an RMS.

Finally, in the hierarchy, the lower level of the manufacturing criterion can be associated to many relevant criteria according to both literature on design [18,21] and on operational [16,30] aspects. To support both the understanding and the engagement of practitioners, the criteria identified in literature have been sorted and hierarchized as follows:

- products, whose lower level is composed of: (i) capability to introduce new product families, (ii) capability to adapt product variety, (iii) effort required to adapt the process after a new product has been designed (product-process design alignment), and (iv) properties of the product in terms of safety and quality
- materials
- process/equipment, in terms of (based on [18]): quality (Research & Development activities and/or test and rework activities), convertibility and scalability. These last two items are extremely relevant when comparing RMS to traditional systems
- buildings, in terms of convertibility and scalability at network level. With this criterion, the network effects of the design of RMS have been included based on the interest shown in previous projects by some companies having factories in multiple locations

The following figure (Fig. 4) represents the lower level of convertibility and scalability at both process level (Fig. 4.a) and network level (Fig. 4.b).

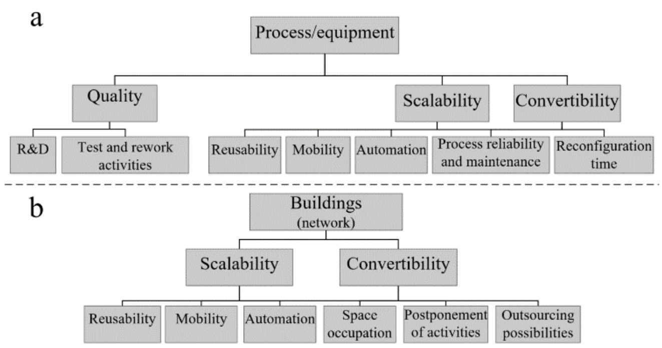


Fig. 4. (a) Scalability and convertibility criteria at process level; (b) scalability and convertibility criteria at network level

In Fig. 4, criteria such as the reusability and the mobility of the solution, and/or the reconfiguration time are relevant to support practitioners in taking a system lifecycle perspective [18,20,21].

Overall, the proposed hierarchy aims to engage practitioners by providing them full awareness of potentialities and requirements led by the introduction of RMS. Potentially, any manufacturing company can use such hierarchy. Then, the hierarchy can be customised by applying the tool described in section 4.

4. A practical tool for the comparison of concept designs of RMS

A tool combining Analytical Hierarchical Process (AHP) and Pugh Matrix methods for fast and effective comparison of concept designs of RMS is proposed. AHP and Pugh Matrix have been combined together for their simplicity and rapid and effective implementation. Furthermore, due to: (i) the variety and complexity of criteria involved and (ii) the impossibility to provide exact measures of criteria at this strategic stage of the design, the combination of these two methods ensures an adequate comprehensive evaluation of concepts and leads to actual figures to be used to justify decision making choices. Overall, the tool allows for initial comparison of concepts, in a design phase where financial figures and other KPIs may not be possible to evaluate yet.

With regard to the AHP method, it is selected as suitable tool for the prioritisation of criteria for the following motivations. Firstly, the priority given to each individual criterion within the hierarchy described in section 3 is company specific. Secondly, there is a multitude of aspects and long-term effects that need to be considered, thus priorities should be given to both qualitative and quantitative criteria. Thirdly, given the broad nature and scope of such criteria, at this stage of RMS design their quantification would be too complex and time consuming. Finally, the AHP represents a straightforward method when shared and comprehensive evaluations need to be made.

The AHP method allows measures of intangible criteria through pairwise comparisons and relies on the judgements of experts to derive priority scales. The comparisons are made using a scale of absolute judgements that express the dominancy of criteria with respect to the others [31]. The AHP method can incorporate multiple quantitative and qualitative criteria in a meaningful and rational way [32].

To ensure rapid and effective comparison of concept designs of RMS, the Pugh Matrix has been selected.

With regard to the Pugh Matrix, it is a method which like AHP relies on expert judgements, it utilises a matrix with columns - representing detailing concepts - and rows - indicating decision criteria. Concepts are compared with each other in a practical and fast way and insights to the concepts that are decidedly better than the others are provided [12].

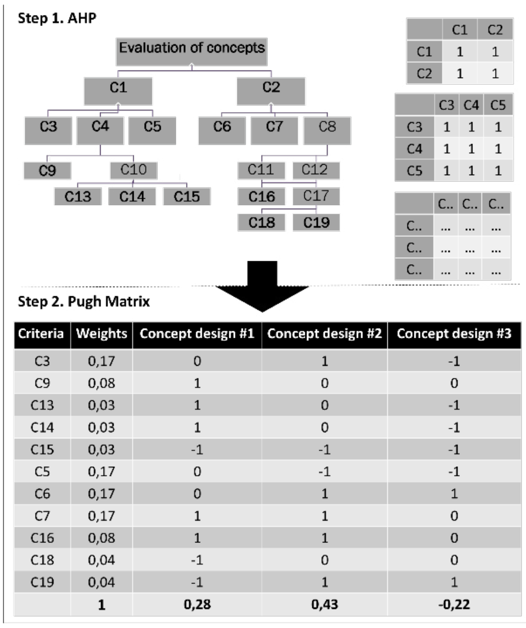
Despite its simplicity, the Pugh Matrix method does not allow for criteria to be given weights [12] and for this reason this study suggests practitioners to combine it with the AHP. To the best of authors' knowledge, in RMS literature there is no study that has used the Pugh Matrix method for any specific subject.

The tool for the comparison of concept designs of RMS is hereafter described.

Firstly, the AHP method is implemented by asking selected company experts to compare the criteria of the hierarchy so to calculate company-specific weights. When selecting experts, it is highly recommended that the company includes at least one person from each of the following categories: (i) process and product experts (designers of manufacturing system and product), (ii) production and factory managers, and (iii) members from strategic departments (e.g. investment department). Following the AHP methodology, the comparison between criteria is a straightforward step, however, to increase its effectiveness, experts should meet in person and get a shared understanding of the hierarchy (thus, of the potentialities of RMS). Afterwards, they are asked to agree on scores given at each individual comparison (pairwise comparisons). By simply following the instructions of a pre-set Excel spreadsheet, through their comparisons, experts obtain final weights for the criteria.

Secondly and lastly, the Pugh Matrix method is implemented in another spreadsheet where the weighted criteria resulting from the implementation of the AHP are automatically reported. Thus, experts can compare concept designs with each other and/or with traditional systems. At this stage (where financial figures and other KPIs may not be possible to evaluate yet), they are only required to make relative comparisons between concept designs by stating if a specific design is either better (+1 score), worst (-1 score) than another one, or if the two designs are indifferent (0 scores). Afterwards, the scores are automatically adjusted based on the weights of the criteria obtained from the AHP method. Based on the scores, the company gets the overall evaluation of each individual concept design (which is simply the summation of the weighted scores obtained at the previous stage). The concept design that obtains the highest score is thus the best alternative considering the weights derived from the AHP. However, the purpose of doing the comparison may not only be selecting the best concept, but rather to determine why certain concepts are better than others and modify the existing concepts to form even better concepts.

The following figure (Fig. 5) illustrates the operation logic of the tool: in a first step, the criteria are weighted through the AHP method, in a second step, they are used in the Pugh Matrix to evaluate concept designs of RMS. The last row of the matrix provides the value of each concept design option. In this example, the hierarchy has been simplified compared to the one described in section 3 to reduce the complexity of the figure).



	C1	C2
C1	1	1
C2	1	1

	C3	C4	C5
C3	1	1	1
C4	1	1	1
C5	1	1	1

	C..	C..	C..
C..	…	…	…
C..	…	…	…
C..	…	…	…

Criteria	Weights	Concept design #1	Concept design #2	Concept design #3
C3	0,17	0	1	-1
C9	0,08	1	0	0
C13	0,03	1	0	-1
C14	0,03	1	0	-1
C15	0,03	-1	-1	-1
C5	0,17	0	-1	-1
C6	0,17	0	1	1
C7	0,17	1	1	0
C16	0,08	1	1	0
C18	0,04	-1	0	0
C19	0,04	-1	1	1
	1	**0,28**	**0,43**	**-0,22**

Fig. 5. An illustration of the operation logic of the tool for the comparison of concept designs of RMS

In subsequent detailed stages of RMS design, selected RMS concepts might be assessed based on their actual effects on performances. Compared to the initial design, at these more specific stages, KPIs could be more easily calculated and then prioritized through a different use of the AHP method (see for example [33,34]).

5. Conclusions

The most difficult stage in RMS design is the initial justification of the investment, in which it is critical to reach the engagement of the stakeholders required to ensure the successful implementation of the whole design project within the manufacturing company. Specifically, engaging the relevant stakeholders within a company requires them to adopt a system lifecycle perspective and consider the uncertain nature of future requirements.

This study aims to support the initial design of RMS, providing a tool for the comparison of concept designs of RMS. To ensure the generalizability of the tool and the engagement of practitioners, a general context-independent hierarchy has been proposed based on both literature and authors' experience from previous projects with companies. To ensure the practicality of the tool, a tool combining Analytical Hierarchical Process (AHP) and Pugh Matrix methods is described. The tool also stimulates practitioners to adopt a lifecycle perspective and to consider the uncertainty of future requirements so to further engage them into the design of a RMS. The tool has been empirically validated. Compared to extant literature, this study is the first attempt to combine AHP and Pugh Matrix methods.

In future research, the authors plan to illustrate the implementation of the tool in manufacturing contexts, with the specific intent of showing how the use of the tool might lead to very different choices, based on company-specific needs.

Given its focus on the evaluation of concept designs of RMS, this work does not provide technical indications on how companies should develop concept designs of RMS. Further research could address this aspect. Considering the ongoing 4th industrial revolution, an interesting direction for further research might be investigating the combined design of RMS and Information and Communication Technology architecture. This has been partially pointed in this research and certainly deserves further investigation.

Acknowledgments

This research was done in the REKON project, funded by the Danish Industry Foundation. Partners in the project are Aalborg University, Jönköping University, the University of Southern Denmark, and The Danish Technological Institute. REKON is funded by The Danish Industry Foundation.

References

[1] Deif AM, ElMaraghy WH. A Systematic Design Approach for Reconfigurable Manufacturing Systems. Adv Des 2006:219–28. https://doi.org/10.1007/1-84628-210-1_18.
[2] Maganha I, Silva C, Ferreira LMDF. The sequence of implementation of reconfigurability core characteristics in manufacturing systems. J Manuf Technol Manag 2020;(published. https://doi.org/10.1108/JMTM-09-2019-0342.
[3] Khanna K, Kumar R. Reconfigurable manufacturing system: a state-of-the-art review. Benchmarking 2019;26:2608–35. https://doi.org/10.1108/BIJ-05-2018-0140.
[4] Napoleone A, Andersen AL, Brunoe TD, Nielsen K, Boldt S, Rösiö C, et al. Towards an Industry-Applicable Design Methodology for Developing Reconfigurable Manufacturing. IFIP Adv Inf Commun Technol 2020;591 IFIP:449–56. https://doi.org/10.1007/978-3-030-57993-7_51.
[5] Saliba MA, Azzopardi S, Pace C, Zammit D. A heuristic approach to module synthesis in the design of reconfigurable manufacturing systems. Int J Adv Manuf Technol 2019:4337–59. https://doi.org/10.1007/s00170-019-03444-4.
[6] Andersen A-L, Brunoe TD, Nielsen K, Rösiö C. Towards a generic design method for reconfigurable manufacturing systems. J Manuf Syst 2017;42:179–95. https://doi.org/10.1016/j.jmsy.2016.11.006.
[7] Bortolini M, Galizia FG, Mora C. Reconfigurable manufacturing systems: Literature review and research trend. J Manuf Syst 2018;49:93–106. https://doi.org/10.1016/j.jmsy.2018.09.005.
[8] Napoleone A, Pozzetti A, Macchi M. A framework to manage reconfigurability in manufacturing. Int J Prod Res 2018;56:3815–37. https://doi.org/10.1080/00207543.2018.1437286.
[9] Boldt S, Rösiö C. Evaluation of Reconfigurability in Brownfield Manufacturing Development. 9th Swedish Prod. Symp. Knowledge-Intensive Prod. Realis. Co-operation Futur. Sustain. Compet. - Jönköping Univ. Jönköping, Sweden, 2020.
[10] Andersen A-L, Nielsen K, Brunoe TD. Prerequisites and Barriers for the Development of Reconfigurable Manufacturing Systems for High Speed Ramp-up. Procedia CIRP 2016;51:7–12. https://doi.org/10.1016/j.procir.2016.05.043.
[11] Rösiö C, Säfsten K. Reconfigurable production system design – theoretical and practical challenges. J Manuf Technol Manag 2013;24:998–1018. https://doi.org/10.1108/JMTM-02-2012-0021.
[12] Kremer G, Tauhid S. Concept selection methods - A literature review from 1980 to 2008. Int J Des Eng 2008;1:243–77. https://doi.org/10.1504/IJDE.2008.023764.
[13] Durach CF, Kembro J, Wieland A. A New Paradigm for Systematic

Literature Reviews in Supply Chain Management. J Supply Chain Manag 2017;53:67–85. https://doi.org/10.1111/jscm.12145.
[14] Abdi MR, Labib AW. Performance evaluation of reconfigurable manufacturing systems via holonic architecture and the analytic network process. Int J Prod Res 2011;49:1319–35. https://doi.org/10.1080/00207543.2010.520989.
[15] Zhou B, Chen C. Multi-level Fuzzy Comprehensive Evaluations for Rapid Manufacturing Systems. 2010 Seventh Int. Conf. Fuzzy Syst. Knowl. Discov. (FSKD 2010), IEEE; 2010, p. 1315–9.
[16] Garbie IH. Measurement of reconfiguration level based on manufacturing firms design and agility. Proc. 2007 Ind. Eng. Res. Conf. G. Bayraksan, W. Lin, Y. Son, R. Wysk, eds. Meas., 2007, p. 76–81.
[17] Abdi MR, Labib AWAW. A design strategy for reconfigurable manufacturing systems (RMSs) using analytical hierarchical process (AHP): A case study. Int J Prod Res 2003;41:2273–99. https://doi.org/10.1080/0020754031000077266.
[18] Abdi MR, Labib AW. Feasibility study of the tactical design justification for reconfigurable manufacturing systems using the fuzzy analytical hierarchical process. Int J Prod Res 2004;42:3055–76. https://doi.org/10.1080/00207540410001696041.
[19] Park JM. Improved methodology for RMS adaptability evaluation. Int J Precis Eng Manuf 2017;18:1537–46. https://doi.org/10.1007/s12541-017-0182-5.
[20] Cheikh SBEN, Hajri-gabouj S, Darmoul S. Reconfiguring manufacturing systems using an analytic hierarchy process with strategic and operational indicators. Int. Conf. Ind. Eng. Oper. Manag., IEEE; 2015.
[21] Singh RK, Khilwani N, Tiwari MK. Justification for the selection of a reconfigurable manufacturing system: a fuzzy analytical hierarchy based approach. Int J Prod Res 2007;45:3165–90. https://doi.org/10.1080/00207540600844043.
[22] Andersen AL, Brunoe TD, Nielsen K, Bejlegaard M. Evaluating the investment feasibility and industrial implementation of changeable and reconfigurable manufacturing concepts. J Manuf Technol Manag 2018;29:449–77. https://doi.org/10.1108/JMTM-03-2017-0039.
[23] Galan R, Racero J, Eguia I, Garcia JM. A systematic approach for product families formation in Reconfigurable Manufacturing Systems. Robot Comput Integr Manuf 2007;23:489–502. https://doi.org/10.1016/j.rcim.2006.06.001.
[24] Rehman AU, Babu AS. Evaluation of reconfigured manufacturing systems: an AHP framework. Int J Product Qual Manag 2009;4:228. https://doi.org/10.1504/IJPQM.2009.023189.
[25] Lee S, Ryu K, Shin M. The Development of Simulation Model for Self-reconfigurable Manufacturing System Considering Sustainability Factors. Procedia Manuf 2017;11:1085–92. https://doi.org/10.1016/j.promfg.2017.07.226.
[26] Battaïa O, Benyoucef L, Delorme X, Dolgui A, Thevenin S. Sustainable and Energy Efficient Reconfigurable Manufacturing Systems. Reconfigurable Manuf. Syst. From Des. to Implement., 2020, p. 179–91. https://doi.org/10.1007/978-3-030-28782-5_9.
[27] Cheikh S Ben, Hajri-Gabouj S, Darmoul S. Manufacturing configuration selection under arduous working conditions: A multi-criteria decision approach. Proc. Int. Conf. Ind. Eng. Oper. Manag., 2016, p. 1280–91.
[28] Napoleone A, Macchi M, Pozzetti A. A review on the characteristics of cyber-physical systems for the future smart factories. J Manuf Syst 2020;54. https://doi.org/10.1016/j.jmsy.2020.01.007.
[29] Ashrafian A, Powell DJ, Ingvaldsen JA, Dreyer HC, Holtskog H, Schütz P, et al. Sketching the Landscape for Lean Digital Transformation. IFIP Adv. Inf. Commun. Technol., vol. 566, 2019, p. 29–36. https://doi.org/10.1007/978-3-030-30000-5_4.
[30] Abdi MR. Layout configuration selection for reconfigurable manufacturing systems using the fuzzy AHP. Int J Manuf Technol Manag 2009;17:149–65. https://doi.org/10.1504/IJMTM.2009.023783.
[31] Saaty TL. Decision making with the analytic hierarchy process. Int J Serv Sci 2008;1:83–98.
[32] Teehankee B. The Analytic Hierarchy Process : Capturing Quantitative and Qualitative Criteria for Balanced Decision-making 1. 3rd Natl. Conf. OR Soc. Philipp., 2018.
[33] Maier-Speredelozzi V, Hu SJ. Selecting manufacturing system configurations based on performance using AHP. Soc Manuf Eng - Tech Pap 2002:1–8.
[34] Wang GX, Huang SH, Yan Y, Du JJ. Reconfiguration schemes evaluation based on preference ranking of key characteristics of reconfigurable manufacturing systems. Int J Adv Manuf Technol 2016;89:2231–2249. https://doi.org/10.1007/s00170-016-9243-7.