Reconfigurable Manufacturing: An Investigation of Diagnosability Requirements, Enabling Technologies and Applications in Industry

Alessia Napoleone[1], Brendan P. Sullivan[2], Elias Arias-Nava[3], Ann-Louise Andersen[1]

[1] Department of Materials and Production, Aalborg University, Aalborg, Denmark
[2] Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy
[3] Department of Industrial and Operations Engineering, Instituto Tecnologico Autonomo de Mexico, Mexico City, Mexico
alna@mp.aau.dk

Abstract. In the dynamic environment of today's manufacturing industry, companies need to be changeable, i.e. capable of adapting to changes quickly and cost-effectively. In this context, the diagnosability characteristic, allowing fast and economic ramp-ups of new manufacturing settings, becomes particularly relevant. Depending on their diagnosability requirements, companies can exploit different technologies and applications. In this study, five diagnosability requirements have been identified. Through a literature review, the five requirements have been further investigated; thus, the extent to which these five requirements can be fulfilled, and their enabling technologies and applications has been specified. Finally, a case study has been conducted to show how diagnosability requirements are fulfilled differently in three manufacturing contexts.

Keywords: Changeable Manufacturing, Reconfigurable Manufacturing System, Diagnosability, Industry 4.0

1 Introduction

Manufacturing companies incessantly face challenges due to evolving market requirements, governmental regulations, dynamic shifts in technology and sustainability requirements. In response to these challenges, companies are required to change their processes and manufacturing systems. To this end, the term changeability has been used in literature as an umbrella concept to refer to the generic capability of a system to dynamically change as quickly, effectively and economically as possible [3, 20]. At the manufacturing system level, changeability can be fulfilled through Reconfigurable Manufacturing Systems (RMS) [3]. RMSs are capable to repeatedly change and/or rearrange their components in a cost-effective way in order to quickly adjust production capacity and functionality to accommodate evolving requirements [15]. To this purpose, RMSs can be deconstructed according to six core characteristics: modularity, integrability, diagnosability, scalability, convertibility and customization [9]. Amongst these characteristics, diagnosability allows fast and eventually automatic fulfillment of one or more of the following requirements:

- Req. 1. Avoid quality and reliability problems [4, 12, 19];
- Req. 2. Detect and localize quality and reliability problems [9, 18];
- Req. 3. Identify causes of quality and reliability problems [9, 19];
- Req. 4. Correct quality and reliability problems (local action) [4, 21];
- Req. 5. Identify alternative solutions for error or failure recovery (systemic action) [11].

Two reasons make diagnosability particularly relevant. First, as reconfigurations of manufacturing systems should be quick and economic, diagnosability allows companies to implement more frequent reconfigurations by ensuring that the system is capable to quickly reach stable production after reconfigurations. Secondly, Industry 4.0, leading to the increasing availability and exploitation of high quantities of digital data, promises to support companies in developing diagnosability. Therefore, this paper focuses on the diagnosability characteristic of RMSs and addresses the following two research questions: *"How can the five diagnosability requirements be fulfilled in different manufacturing contexts?" and "which technologies and applications enable the five diagnosability requirements?"*

Through literature review, a framework for mapping the five diagnosability requirements and enabling technologies and applications is provided in this study. Subsequently, through a case study, the framework is applied to three cases to show how diagnosability requirements are fulfilled in these contexts.

2 Literature review

A literature search was conducted in Scopus, combining the key-words "diagnosability" and "manufacturing system". Literature published after 2011 was considered. Through this search, 18 papers were selected and used for the construction of the proposed framework due to their relevancy, as detailed in the remainder. These 18 papers were selected and classified based on the following criteria: (i) the publication referenced diagnosability requirements, meaning any of the five requirements (from req. 1 to req. 5) listed in Section 1; and/or (ii) the publication suggested technologies and applications enabling the fulfillment of the stated requirements.

Hereafter, the results of the literature review are summarized.

Diagnosability requirements publications: three papers referenced req. 1 (avoid quality and reliability problems) [9, 15, 19]; 11 papers referenced req. 2 (detect and localize quality and reliability problems) [1, 4, 18, 5–9, 13, 14, 16]; 14 papers referenced req. 3 (identify causes of quality and reliability problems) [2, 4, 17–19, 21, 5–11, 13]; five papers referenced req. 4 (correct quality and reliability problems) [4, 6, 10, 13, 21]; and, one paper referenced req. 5 (identify alternative solutions for error or failure recovery) [11].

Technologies and applications publications: from the 18 papers identified in the review, three papers referenced reconfigurable inspection resources [8, 18, 19]; one paper referenced units designed for replacement [17]; and one paper referenced built-in redundancy [11]. As a consequence of Industry 4.0, a number of not necessarily recent technologies coupled with new applications can be associated to diagnosability. This includes: sensors [11, 14, 19]; Internet of Things [14]; big data analytics [7, 17]; tracking/monitoring information systems [7–9]; digitally assisted operators [12]; digitally-enabled poka-yoke mechanisms [9, 15]; verification of correct position of products in machines' feeding systems [6, 19]; smart devices [14]; actuators [14].

Fig. 1 summarizes the results of the literature review: diagnosability requirements can be fulfilled to different extents, recurring to a number of technologies and applications. For example, req. 1 can be fulfilled through either manual, semi-automatic or automatic avoidance of problems, exploiting technologies and applications such as digital poka-yoke mechanisms, verification of the correct position of products in machines' feeding systems and digital assistance systems.

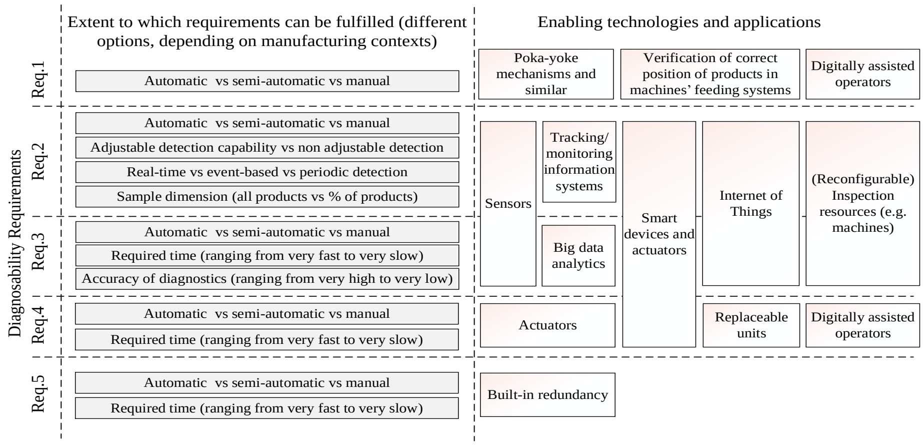


Fig. 1. Diagnosability requirements, extent to which they can be fulfilled, and their enabling technologies and applications

3 Case study

Three companies, which over the past five years have been working to increase their diagnosability and the level of automation within their processes, were analyzed from October 2020 to May 2021.

- Case #1 is involved in the manufacturing of outdoor furniture, producing roughly different 216 products with 800 employees. The facility is equipped with automated robotic stations, manual production stations and various finishing solutions.
- Case #2 designs and manufactures 41 high-precision telecommunications and technological solutions, for commercial, space and defense. The facility with 1200 employees is equipped with automated and manual production processes.
- Case #3 manufactures 11 specialized products for military aircraft, with international operations. Comprised of roughly 850 employees they design and manufacture high-precision products through various automated and manual processes.

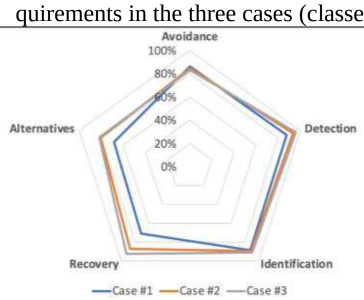
Based on the results of the literature review, a questionnaire comprised of both closed and open-ended questions was built and used for the analysis. Closed-ended questions aimed at the: (i) identification of diagnosability requirements (from req. 1 to req. 5), (ii) identification of technologies and applications supporting diagnosability requirements, and (iii) quantification of the existing level of diagnosability, based on requirements and technologies and applications. Open-ended questions aimed at catching further insights on enabling technologies and applications.

In each case, the production manager (or delegate) was interviewed. To quantify the existing level of diagnosability, closed-ended questions were scored using a Likert scale (5 points scale; 1,3,5,7,9), so the respondent could choose their company's practice level. The lowest levels scored with 1 corresponded to a poor practice, while the highest-level scored with 9 corresponded to a best practice. Finally, an overall measure of the extent to which the five classes of diagnosability requirements are fulfilled was obtained.

4 Results

The results of the case study are summarized in the remainder, where the requirements and the technologies and applications within each case were analyzed and detailed.

Table 1. A measure of the overall level of diagnosability, based on the fulfilment of the five requirements in the three cases (classes of diagnosability requirements are listed in Fig. 1)



	Classes of Diagnosability Requirements				
	Req. 1 - Avoidance	**Req. 2 - Detection**	**Req. 3 - Identification**	**Req. 4 - Recovery**	**Req. 5 -Alternatives**
Case #1 – 80.0%	78.5%	88.6%	83.8%	73.3%	63.6%
Case #2 – 87.5%	**86.3%**	93.4%	89.8%	86.4%	80.7%
Case #3 – 89.1%	85.2%	**94.6%**	**93.2%**	**92.4%**	**82.3%**
Average	83.3%	92.2%	88.9%	84.0%	77.2%
Standard Deviation	0.042	0.032	0.048	0.098	0.104

For each case, the overall level of diagnosability, based on the fulfillment of the five classes of requirements (from req.1 to req. 5), is synthesized in Table 1. As shown in Table 1, Case #3 has generally a higher level of fulfillment of the diagnosability requirements. Moreover, the highest variation between the three cases is observed in req. 5.

An analysis of the extent to which requirements are fulfilled, allowing to better understand how these are fulfilled, is summarized in Table 2. For example, from Table 2 it can be deducted that the highest variation between cases observed in req. 5 can be attributed to differences in the level of automation and the responsiveness of the solutions adopted in the three cases.

Table 2. Extent to which requirements are fulfilled in the three cases

	Case #1	Case #2	Case #3
Req.1	Semi-automatic and manual	Automatic and semi-automatic	Automatic and semi-automatic
Req.2	Semi-automatic and manual Adjustable detection Event-based detection Sample dimensions (% of products)	Automatic and semi-automatic Adjustable detection Event-based detection Sample dimensions (all products)	Automatic and semi-automatic Adjustable detection Event-based detection Sample dimensions (all products)
Req.3	Manual Required time (average/slow) Required accuracy of diagnostics (average)	Semi-automatic and manual Required time (fast) Required accuracy of diagnostics (high)	Semi-automatic and manual Required time (very fast) Required accuracy of diagnostics (very high)
Req.4	Manual Required time (average/slow)	Manual Required time (fast)	Semi-automatic and manual Required time (very fast)
Req.5	Manual Required time (slow)	Semi-automatic and manual Required time (fast)	Semi-automatic and manual Required time (fast)

Finally, different technologies and applications are exploited to fulfill the five diagnosability requirements, as summarized in Table 3.

Table 3. Enabling Technologies and Applications (the list is in alphabetic order) in the three cases (Cases #1, #2 and #3 are indicated in the table respectively with 1, 2 and 3)

Enabling Technology/Application	Req. 1	Req. 2	Req. 3	Req. 4	Req. 5
Actuators				1,2,3	
Augmented reality	3				3
Big data analytics			3		
Built in redundancy					1,2,3
Combination of sensors and IoT					1,2,3
Digitally assisted operators				1,2,3	
Machine-to-machine communication					3
Manufacturing Execution System and control system (Programmable Logic Controllers)	1,2,3		1,2,3	1,2,3	
Poka-yoke mechanism (or similar)	1,2,3				
Reconfigurable inspection resources		1,2,3	1,2,3		
Replaceable units				1,2,3	
Robotics	1,2,3				
Tracking/monitoring information systems	3		3		
Sensors		1,2,3			
Smart devices		1,2,3	1,2,3	1,2,3	
Verification of correct position of products in machine feeding systems	1,2,3				

Five technologies and applications have been added to those identified through the literature review, these are: (i) augmented reality to fulfill req. 1 and req. 5; (ii) machine-to-machine communication to fulfil req. 5; (iii) Manufacturing Execution System and control system to fulfil req. 1 and req. 3; (iv) Programmable Logic Controllers to fulfil req. 4; and (v) robotics, to fulfil req. 1. Moreover, Case #3 shows that the combination of sensors and IoT can be used to support req. 5 (thus, extending the results of the literature review which show – in Fig. 1 - that this technology supports the req. 2 and req. 3). Case #3 also shows that the tracking/monitoring information system can be used to support req. 1 and req. 3 (other than req. 2 as resulting from the literature review).

5 Conclusions

Given the relevance of the diagnosability characteristic in the current manufacturing scenario, this study aimed to uncover and detail five diagnosability requirements (from req. 1 to req. 5) through a literature review and a case study.

The literature review found that the five diagnosability requirements can be fulfilled to different extents, through several technologies and applications. From the literature review, it can be concluded that req. 2 and req. 3 are the currently most investigated, while req. 1, req. 4 and req. 5 deserve further research, especially in the light of new potentialities offered by Industry 4.0.

The case study showed how diagnosability requirements are fulfilled in three different manufacturing companies in disparate manners. The managerial implications of this study lie in the possibility for a company to describe its diagnosability, and eventually identify requirements, and select technologies and applications to improve the diagnosability level. Given the relevance of diagnosability today, further research should aim at building a maturity assessment model based on the results of this investigation. Moreover, technologies and applications should be further investigated through additional empirical research.

A limitation of this study is that the technologies and applications have been roughly treated together, future research should first specify which applications allow companies fulfilling their diagnosability requirements, and then specify the technologies that can be used in the applications. Moreover, the results of the three cases are based on qualitative information collected through interviews, further research should aim at providing unbiased measures of the fulfilment of diagnosability requirements, to then allow a proper investigation of the status of fulfillment of diagnosability requirements in industry.

References

1. Cabasino MP, Giua A, Marcias L, Seatzu C (2012) A comparison among tools for the diagnosability of discrete event systems. IEEE Int Conf Autom Sci Eng 218–223

2. Djaker A, Sekhri L (2016) Structure theory of petri nets to deal with diagnosability of automated manufacturing systems. EEA - Electroteh Electron Autom 64:121–126
3. ElMaraghy HA, Wiendahl H-P (2008) Changeability – An Introduction. Chang Reconfigurable Manuf Syst 3–24
4. Gumasta K, Kumar Gupta S, Benyoucef L, Tiwari MK (2011) Developing a reconfigurability index using multi-attribute utility theory. Int J Prod Res 49:1669–1683
5. Huang A, Badurdeen F, Jawahir IS (2018) Towards Developing Sustainable Reconfigurable Manufacturing Systems. Procedia Manuf 17:1136–1143
6. Jiao Y, Djurdjanovic D (2011) Compensability of errors in product quality in multistage manufacturing processes. J Manuf Syst 30:204–213
7. Jimenez JF, Zambrano-Rey G, Aguirre S, Trentesaux D (2018) Using process-mining for understating the emergence of self-organizing manufacturing systems. IFAC-PapersOnLine 51:1618–1623
8. Koren Y, Gu X, Badurdeen F, Jawahir IS (2018) Sustainable Living Factories for Next Generation Manufacturing. Procedia Manuf 21:26–36
9. Maganha I, Silva C, Ferreira LMDF (2020) The sequence of implementation of reconfigurability core characteristics in manufacturing systems. J Manuf Technol Manag.
10. Marangé P, Philippot A, Pétin JF, Gellot F (2015) Diagnosability evaluation by Model-Checking. IFAC-PapersOnLine 28:308–313
11. Milisavljevic-Syed J, Commuri S, Allen JK, Mistree F (2019) A method for the concurrent design and analysis of networked manufacturing systems. Eng Optim 51:699–717
12. Napoleone A, Andersen A (2020) Reconfigurable Manufacturing: How Shop Floor Digitalisation Supports Operators in Enhancing Diagnosability. In: Advances in Transdisciplinary Engineering – 13:525-536
13. Napoleone A, Pozzetti A, Macchi M (2018) Core Characteristics of Reconfigurability and their Influencing Elements. IFAC-PapersOnLine 51:116–121
14. Pal D, Vain J (2019) A systematic approach on modeling refinement and regression testing of real-time distributed systems. IFAC-PapersOnLine 52:1091–1096
15. Prasad D, Jayswal SC (2019) Assessment of a reconfigurable manufacturing system. Benchmarking
16. Rajaoarisoa L, Sayed-Mouchaweh M (2017) Adaptive online fault diagnosis of manufacturing systems based on DEVS formalism. IFAC-PapersOnLine 50:6825–6830
17. Schmidt KW (2013) Verification of modular diagnosability with local specifications for discrete-event systems. IEEE Trans Syst Man, Cybern Part ASystems Humans 43:1130–1140
18. Shang X, Milisavljevic-Syed J, Huang S, Wang G, Allen JK, Mistree F (2020) A key feature-based method for the configuration design of a reconfigurable inspection system. Int J Prod Res
19. Singh A, Asjad M, Gupta P, Khan ZA, Siddiquee AN (2021) Measuring the Relative Importance of Reconfigurable Manufacturing System (RMS) Using Best–Worst Method (BWM). Springer Singapore
20. Sullivan BP, Rossi M, Terzi S (2018) A Review of Changeability in Complex Engineering Systems. In: IFAC-PapersOnLine. pp 1567–1572
21. Wang GX, Huang SH, Yan Y, Du JJ (2017) Reconfiguration schemes evaluation based on preference ranking of key characteristics of reconfigurable manufacturing systems. Int J Adv Manuf Technol 89:2231–2249