Towards Developing Sustainable Reconfigurable Manufacturing Systems

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Notes/Citation Information
Published in *Procedia Manufacturing*, v. 17, p. 1136-1143.

Digital Object Identifier (DOI)
https://doi.org/10.1016/j.promfg.2018.10.024

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 17 (2018) 1136–1143

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

28th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2018), June 11-14, 2018, Columbus, OH, USA

Towards Developing Sustainable Reconfigurable Manufacturing Systems

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Abstract

This paper aims to examine the sustainable manufacturing performance of Reconfigurable Manufacturing Systems (RMSs) using existing sustainable manufacturing metrics. RMS has six key characteristics including modularity, integrability, customization, scalability, convertibility, and diagnosability. In this paper, 'convertibility' is quantified by considering configuration convertibility, machine convertibility, and material handling device convertibility from the RMS perspective. In addition, the performance of RMSs with different convertibility levels is also evaluated by using sustainable manufacturing metrics. A numerical example is used to demonstrate the computational approach. Results of the analysis are used to show how sustainable manufacturing performance of RMS changes as system convertibility varies. The findings show that RMS sustainable manufacturing performance can be improved by selecting a suitable level of convertibility.

Keywords: Reconfigurable Manufcuturing Systems (RMS); sustainable manufacturing; convertibility

1. Introduction

In today's global market, manufacturers face an increasingly complex environment due to scarcity of natural resources, stricter regulations and changing customer demand. Therefore, it is inevitable that manufacturers implement strategies to meet these challenges through product changes, manufacturing process changes, and technology changes, etc. As customers demand more and more personalized products, the need for customization and new product

10.1016/j.promfg.2018.10.024

development are also increasing. Thus, manufacturers must explore solutions to rapidly and efficiently handle demand for new and customized products, and frequent demand fluctuations to stay competitive.

Traditional manufacturing systems such as dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS) are unable to meet these requirements and provide the level of responsiveness at a reasonable/acceptable cost [1]. DMLs are typically designed to produce a single product at high production rate but cannot meet the requirements for variety, short product lifecycles, and demand changes. When DMLs operate below full capacity, the line is underutilized leading to losses [2]. FMS consist of computer numerically controlled (CNC) machines and other programmable automation designed to produce a variety of products [3]. Despite this advantage, FMS are not widely used due to the large investment required compared to DML. The production capacity of FMS is also typically lower than that of DML. Thus, while DMLs and FMSs have their own benefits, none are able to provide the features required to meet the needs of rapidly changing markets with increasing demand for customized products. Reconfigurable Manufacturing Systems (RMS) can be implemented to quickly respond to these emerging challenges by quickly and efficiently adjusting production capacity and functionality. The concept of RMS was introduced by Koren et al. [4] in the 1990s to combine the high production rate of DML and flexibility of FMS. RMS is defined as “a system designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements” [5]. Compared to traditional manufacturing systems, RMS can efficiently produce multiple items in a product family and those from different generations over its lifetime to meet demand in different markets. This is enabled through six RMS core characteristics: modularity, integrability, customization, convertibility, scalability, and diagnosability. These characteristics are used to design the whole production system including machines, controllers, and control software, etc. All major components in the manufacturing system, such as structural elements, axes, controls, software, and tooling are made modular. Integrability is enabled by the capability to integrate all the modular components into a system to provide required capabilities. Customization refers to the customization of machines and system for the production of a part/product family for cost reduction in system and machine [1]. Convertibility and scalability refer to adjusting the functionality and capacity of the system and machines [1]. Diagnosability, on the other hand, refers to the ability to detect machine failure and identify causes for unacceptable part/product quality [1]. With these characteristics, RMS provide manufacturers the capability to make rapid system changes and respond to changing market conditions.

On the other hand, the concept of sustainable manufacturing, which has emerged over the past 40 years [6], is becoming increasingly important to ensure resources in manufacturing are used in a cost-efficient and environmentally responsible manner while considering implications for all stakeholders. One of the commonly referred to definitions for sustainable manufacturing is that proposed by the U.S. Department of Commerce, which describes it as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [7]. Adapting this definition, Jawahir et al. [8] stressed that “sustainable manufacturing at product, process and system levels must: demonstrate reduced negative environmental impacts, offer improved energy and resource efficiency, generate minimum quantity of waste, provide operational personnel health while maintaining and/or improving the product and process quality with the overall life-cycle cost benefits”. Sustainable manufacturing aims to provide sustainable benefits to all the stakeholders. Thus, the three pillars of economic, environmental, societal aspects must be considered. Further, the total lifecycle of manufactured products, including the four lifecycle stages (pre-manufacturing, manufacturing, use and post-use) must also be considered. The 6R concept (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture) needs to be incorporated for a multiple lifecycle closed-loop material flow [9].

RMS has significant potential to meet future manufacturing requirements. However, very few studies investigate if and how RMS can contribute to enhance sustainable manufacturing performance with the consideration of factors discussed in the previous paragraph. This work aims to evaluate how RMS influences sustainable manufacturing performance by examining the RMS characteristics, and their potential benefits, using previously developed sustainable manufacturing metrics. As an initial step, ‘convertibility’ is quantified by considering configuration convertibility, machine convertibility, and material handling device convertibility from the RMS perspective. In addition, RMS performance with different convertibility levels is assessed using the sustainable manufacturing metrics. A numerical example is used to demonstrate the findings. The comparison of these results is used to determine how RMS sustainable manufacturing performance changes as convertibility varies.

The paper is organized as follows. Section 2 provides a literature review on Reconfigurable Manufacturing Systems, some studies investigating the sustainable manufacturing aspects of RMS and sustainable manufacturing performance evaluation. Section 3 describes the methodology for evaluating convertibility from RMS and sustainable manufacturing metrics perspectives. Application of the proposed methods is presented using a numerical example and results are compared in Section 4. Conclusions and future work are covered in Section 5.

2. Literature review

A review of the current state of RMS, prior work addressing RMS and sustainable manufacturing and existing methods to evaluate sustainable manufacturing performance are presented in this section.

2.1. Reconfigurable manufacturing system (RMS)

RMS are designed to improve the system responsiveness to rapidly respond to market changes. RMS allow to changing system structure (including hardware and software components) rapidly and cost-efficiently through its characteristics of modularity, integrability, customization, convertibility, scalability, and diagnosability [10]. The influence of these characteristics on RMS is discussed by Mehrabi et al. [11, 12]. Wang and Koren [13] have presented a systematic approach for scalability planning to add the exact capacity needed by simultaneously change the system configuration and rebalance the reconfigured system. The proposed approach was examined and validated in an industrial case study. In their work, only the total number of machines is considered as the objective. However, many other factors such as labor, cost, tool cost, energy consumption, emission, etc., need to be considered when determining scalability requirements. Spicer et al. [14] established the need for scalable machines and a basis for evaluating and describing them. Application metrics including capacity increment size, lead time, cost per unit of capacity, and floor space per unit of capacity, were defined and an architecture for scalable machines was presented. The optimal number of modules to be included on a modular scalable machine was determined based on a mathematical approach [14]. Koren et al. [15] developed design-for-scalability principles and elaborated the economic value of scalability in RMS. They developed a systematic approach for scalability planning which can be used to predict the capacity needed to meet the market demand. The total number of machines and the system throughput was considered as the optimization objectives. As one of the flexibility aspects in RMS, convertibility expresses the ability of a system to change the functionality or move from one product to another. Maier-Speredelozzi et al. [16] proposed metrics to quantify convertibility for different manufacturing systems considering system configuration, machine configuration, and material handling device configuration. One drawback of this method is the subjective evaluation of machine and material handling device configurations. Convertibility indicators for a mixed-model assembly line were proposed by Lafou et al. [17] where new metrics to quantify system convertibility by integrating product and process information is presented. They presented an automotive industry case study to demonstrate the proposed method. Chinnathai et al. [18] discuss convertibility for high variety production in an automated assembly system. System convertibility was measured considering equipment and layout convertibility with equal weight. System constituent components and system layout were evaluated to assess contribution to the system. The proposed approach was demonstrated through a conceptual design of a battery module assembly system.

2.2. Sustainable manufacturing through RMS

Most existing literature on RMS focus on assessing the manufacturing system performance from an economic aspect. Few studies evaluate the RMS performance from sustainable manufacturing perspective that considers economic, environmental and societal aspects simultaneously. Bi [19] has addressed how to connect RMS to sustainable manufacturing from the viewpoint of manufacturing sustainability. In his work, some research directions were identified which will lead to a solution of sustainable manufacturing. To achieve this objective, first, a brief description of today's manufacturing environment was provided. Second, the requirements of sustainability were discussed, and the relevant researches on system sustainability were surveyed. Third, the reconfigurable system paradigm was focused, and the gaps between a reconfigurable manufacturing system and a sustainable manufacturing system were discussed [19]. Koren et al. [20] examined the significance of developing next generation manufacturing systems as the basis for sustainable living factories. They discuss how to adapt, integrate RMS characteristics with the principles of sustainable manufacturing for value creation for all stakeholders. Although these studies discuss how to incorporate sustainable manufacturing requirements in RMS, none presents analytical methods or case studies.

2.3. Sustainable manufacturing performance evaluation

As mentioned in the introduction section, sustainable manufacturing should consider the integration of product, process, and system level. In a manufacturing system, multiple manufacturing processes are combined into workstations and several workstations are combined to create a production line for manufacturing product. Therefore, product, process, and systems are interrelated and influence each other. Here the some of the most comprehensive sustainable manufacturing performance evaluation methods are reviewed to assist with evaluating RMS. A product sustainability assessment method, known as *ProdSI*, is proposed by Shuaib et al. [21]. The index consists of a set of metrics covering the three pillars of sustainability, total lifecycle and 6R concept. Correspondingly, Lu [22] proposed a set of process sustainability metrics which considered manufacturing cost, environmental impact, waste management, energy consumption, operational safety and personnel health. These two methods can be used to assess manufacturing sustainability at product and process levels, respectively. System level sustainability can be evaluated by integrating metrics from product and process levels. Huang and Badurdeen [23] proposed a comprehensive set of metrics for the production line and plant levels following a five-stage metrics hierarchy (individual metrics, sub-clusters, clusters, sub-index and index). The 6R concept, total lifecycle emphasis, and the three pillars of sustainability are considered for selecting relevant metrics. Finally, the metrics are integrated to develop an index for production line and plant level sustainability assessment and demonstrated using a numerical example for line level sustainable manufacturing performance evaluation [23]. Faulkner et al. [24] presented a sustainability evaluation method at production line level where a comprehensive methodology, known as sustainable value stream mapping (Sus-VSM), is proposed to assess manufacturing sustainability performance. As a by-product, the suitable sustainability metrics and methods to visualize them are identified. This approach is also demonstrated through application to an industry case study. However, metrics development in [24] does not integrate total lifecycle focus or 6Rs. All these reviewed evaluation methods provide a foundation to assess the sustainable manufacturing performance of RMS.

3. Methodology

The scope of this research is to explore RMS characteristics to assess how sustainable manufacturing performance varies as that characteristic changes. The most prominent feature of RMS is the flexibility it offers to rapidly respond to market changes. Flexibility is enabled by both convertibility and scalability [25]. In this work, convertibility is selected as an example to present the impacts on sustainable manufacturing performance due to different convertibility levels. The impact on RMS due to different convertibility levels can be evaluated from two perspectives as presented in the sections below: RMS and sustainable manufacturing.

3.1. System convertibility assessment from RMS perspective

The convertibility is defined as “the capability of a system to rapidly adjust production functionality or change from one product to another” [16]. The manufacturing systems are made up of machines which are connected by material handling devices. Therefore, the system convertibility can be related to system configuration, machines, and material handling devices. The most referred to calculation method of convertibility is proposed by Maier-Speredelozzi [16] where overall system convertibility is assessed as shown in Equation (1).

$$C_S = w_1 C_C + w_2 C_M + w_3 C_H \tag{1}$$

where C_C, C_M, and C_H are convertibility metrics associated with the configuration, machine, and material handling devices, respectively. The weights w_1, w_2, w_3 denote the relative importance of each term in the equation and can be adjusted. Based on the machine, their layouts and the material handling devices, the manufacturing system convertibility can be evaluated using the equation.

Configuration convertibility can be measured by considering the minimum increment of conversion, routing connections, and number of replicated machines, preliminary assessment of configuration convertibility, and total number of machines. Minimum increment conversion is used to select preferred manufacturing system configurations and it is also an important indicator of how quickly new or different products can be introduced. For example, full serial configuration has a minimum increment of conversion of 1.00, or 100%, that is, in order to introduce a new product, the entire line must be shut down, changed over, and restarted. Routing connections is determined by including connections between machines as well as connections to an input and output station. Number of replicated machines dictates the number of part types that can be produced without requiring changeovers [16]. For the pure parallel configuration of machines, configuration convertibility is defined as having a value of 10. The full serial configuration of machines will have a configuration convertibility value of 1. This implies that configuration convertibility can range from 1-10 [16] and can be measured by the Equations (2) & (3).

$$C'_C = (R * X)/I \tag{2}$$

$$C_C = 1 + \frac{Log(\frac{C'_C}{C'_{c,serial}})}{Log\left(\frac{C'_{C,K-parallel}}{C'_{C,K-serial}}\right) * \frac{1}{9}} \tag{3}$$

where *R* denotes the number of routing connections, *X* denotes the minimum number of replicated machines, *I* denotes the minimum increment of conversion and *K* is the maximum number of machines in the system.

Machine convertibility can also affect the system convertibility as presented in Equation (4) where C'_M is the machine convertibility for each individual machine and *N* is the number of the machines in the system.

$$C_M = \frac{\sum_{i=1}^{n} C'_M}{N} \tag{4}$$

The machine convertibility is determined by each individual machine in the system. The convertibility of each individual machine (C'_M) can be evaluated by considering some features: (1) equipped with automatic tool changer or multi-head spindle; (2) easily reprogrammed with flexible software; (3) modular with flexible hardware components; (4) equipped with flexible fixturing capacity; (5) equipped with large capacity tool magazine [16]. Each individual machine can be evaluated according to the features listed above by assigning a value from 1-10. It means that if the individual machine is equipped with automatic tool changer or multi-head spindle and it will be assigned 1. If the machine is equipped with large capacity tool magazine, it will be assigned a value of 10.

Material handling convertibility is an important factor affecting system performance and is determined based on the material handling devices that connects machines. It can be calculated as shown in Equation (5) where C'_H is the material handling convertibility for each material handling device, and M is the total number of material handling devices. Each individual material handling device can be assessed based on the following attributes: a free rout or not; multidirectional; reprogrammable; asynchronous motion; automatic [16]. Each material handling device can be evaluated based on these assessment factors and assigned a value from 1-10.

$$C_H = \frac{\sum_{i=1}^{M} C'_H}{M} \tag{5}$$

System convertibility can be evaluated by calculating configuration convertibility, machine convertibility, and material handling convertibility.

3.2. Sustainable manufacturing performance assessment

Metrics have been introduced at product, process, and systems level for sustainable manufacturing performance evaluation. Production line level [26] sustainable manufacturing metrics can be used to evaluate RMS sustainable manufacturing performance using four steps: metrics measurement, normalization, weighting, and aggregation with equations. Due to the space limit, the calculation equations can be found in [26]. Thus, the metrics are sequentially aggregated after normalization and weighting to compute performance at the sub-cluster, cluster and sub-index levels. Finally, the three sub-indices for economic, environmental and societal performance are aggregated to calculate a production line sustainability index.

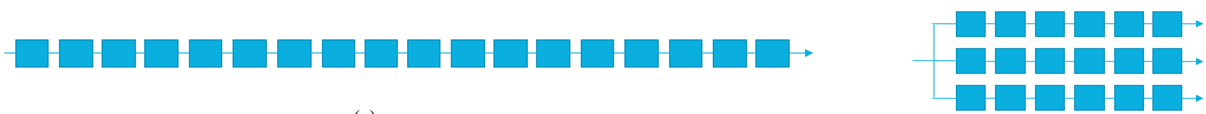
The impact of RMS characteristics on selected production line level economic and environmental sustainability clusters is presented in Fig. 1. As shown, different levels of modularity, integrability, customization, convertibility, scalability, and diagnosability can have an impact on various performance metrics as shown by the ‘X’ marks. For example, changing convertibility could impact lead time, productivity, labor utilization, and on-time delivery from economic aspects. Meanwhile, it could also affect environmental performance metrics such as GHG emissions, liquid waste generation, water and energy usage, and idle energy losses. Other characteristics can also have potential impacts on sustainable manufacturing performance due to influences on various sustainable manufacturing metrics. When considering convertibility, various system configurations, machine convertibility, and material handling devices could have different impacts on energy usage, water consumption, labor and energy cost, etc.

Clusters	Emission			Waste					Water use and efficiency			Energy use and efficiency				Operational performance				Manufacturing cost										
Individual metrics	GHG intensity	Total amount of hazardous gas generated	Total amount of GHG generated	Residual generation intensity	Total amount of liquid waste generated	Percentage of waste recovered	Total amount of solid waste genreated	Total amount of hazardous waste generated	Total amount of water consumption	Percentage of water reused/recycled	Water intensity	total amount of energy usage	Idle energy losses	Percentage of renewable energy usage	Energy intensity	Lead time	Productivity	Labor utilization	Percentage of on time delivery	Labor cost	Material cost	Energy cost	Water cost	Transportation cost	Warehouse cost	Scrap cost	Maintenance cost	Tool cost	Equipment cost	Processing related consumables cost
RMS characteristics: Modularity	X		X	X	X			X	X		X	X	X		X		X	X	X	X		X	X			X		X	X	
RMS characteristics: Integrability													X				X					X	X					X	X	
RMS characteristics: Customization	X		X	X	X			X	X		X	X	X		X	X	X	X	X	X		X	X			X	X	X	X	
RMS characteristics: Convertibility	X		X	X	X			X	X		X	X	X		X	X	X	X	X			X	X	X			X	X	X	
RMS characteristics: Scalability									X		X	X	X		X	X	X	X				X					X	X	X	
RMS characteristics: Diagnosability	X		X		X				X		X	X	X		X		X											X	X	

Fig. 1. Impacts of RMS characteristics on economic and environmental sustainability at production line level

4. Application

The assessment of RMS performance as convertibility changes, and its influence on sustainable manufacturing performance, is demonstrated in this section. Two different configurations are used to compare the convertibility impacts on sustainable manufacturing performance as shown in Fig. 2. Both configurations have eighteen CNC with relatively small tool magazines and manual material handling devices [27].



(a) (b)

Fig. 2. Two configurations for convertibility evaluation

System convertibility can be calculated from equations (1-5) using equal weights and the results are shown in Fig. 3(I). A sub-set of economic and environmental metrics are used to assess sustainable manufacturing performance of the two configurations. Values for metrics are estimated from literature/public sources. Results for the selected sub-clusters, clusters, sub-indices and overall RMS performance computed using equal weights is shown in Fig. 3(II). As can be observed, configuration (b) has a higher convertability score (6.4) compared to that for configuration (a). When sustainable manufacturing performance is considered, configuration (b) has higher a manufacturing cost with a score of 3.33 due to the larger capital investment required compared to configuration (a). However, it rates higher for operational performance (7.89) compared to configuration (a) due to capability to rapidly and efficiently respond to market changes. In addition, configuration (b) has better performance for energy/water use and efficiency with a score of 4.23/5.22 compared to configuration (a) which has values of 4.17/4.33. When the combined economic and environmental performance is considered (index column in Fig.3(II)), configuration (b) has a higher score (5.16) compared to configuration (a) (5.12). Based on these results, configuration (b) with higher convertability also reflects better economic and environmental performance.

Configuration	Number of machine (N)	Machine convertibility (C_M)	Material handling convertibility (C_H)	Replicated machines (X)	Increment of conversion (I)	Routing connections (R)	Configuration convertibility (C_C)	System convertibility (C_S)
(a)	18	5	9	1	1	19	1	5
(b)	18	6	9	3	0.33	21	4.22	6.4

I. Convertability values

Index	(a)	(b)	Sub-Index	(a)	(b)	Clusters	(a)	(b)	Sub-cluster	(a)	(b)	Metrics	Normalized (a)	Normalized (b)	Measured (a)	Measured (b)	Units
Line Sustainability Index	5.12	5.16	Economy	6	5.61	Manufacturing Cost	5	3.33	Direcr cost	5	4.72	Labor cost	5	4.67	2400	2560	$
												Energy cost	5	4	6000	7200	$
												Water cost	5	5.5	4.52	4.068	$
									Indirect cost	5	1.93	Equipment cost	5	1.36	90000	155520	$
												Maintenance cost	5	2.5	3000	4500	$
						Operational Performance	7	7.89	Operational efficiency	6.83	7.89	Lead time	5	4.67	15	16	days
												Productivity	7	9	70	90	%
												Percentage of on-time delivery	8.5	10	85	100	%
			Environment	4.25	4.72	Energy Use and Efficiency	4.17	4.23	Energy content	3.33	3.25	Total amount of energy usage	5	4	12000	14400	kWh
												Idle energy losses	5	5.75	1000	1150	kWh
												Percentage of renewable energy usage	0	0	0	0	%
									Energy efficiency	5	5.20	Energy intensity	5	5.20	12	11.52	kWh/unit
						Other resources use and efficiency	4.33	5.22	Water content	4.33	5.22	Total amount of water consumption	5	6.4	5000	3600	gallon
												Percentage/amount of water reused/recycled	3	3	30	30	%
									Water efficiency			Water intensity	5	6.25	4	2.88	kg/unit

II. Sustainable manufacturing performance

Fig. 3. Comparison of results for two RMS Configurations

Though the assessment here was limited to only economic and environmental metrics, results here show that RMS with different convertibility levels can have variations in their sustainability performance. Therefore, identifying the optimal convertibility level will be an important consideration when designing RMSs which can also enhance sustainable manufacturing performance.

5. Conclusions and future work

RMS can rapidly and efficiently change its configuration to adjust production capacity and functionality to meet market changes. To improve RMS sustainable manufacturing performance, the impacts on the three pillars of sustainability and total product lifecycle performance as well as the ability to implement the 6Rs should be considered simultaneously. In this paper, the current state of art of RMS was reviewed to explore a method for RMS sustainable manufacturing performance evaluation and improvement. The characteristic of RMS 'convertibility' was selected as an example to assess impacts on sustainable manufacturing performance as its changes.

The application of these two convertibility evaluation methods was demonstrated using a numerical example. Though theoretical values were used for metrics and only economic/environmental criteria were considered, the findings help demonstrate that RMS sustainable manufacturing performance can vary as convertibility changes. Similarly, it is likely that other RMS characteristics, too, could have an influence on systems sustainability performance. Therefore, further work is necessary to study the influence of various RMS characteristics, independently as well as considering them simultaneously, on system sustainability performance. Identifying potential impacts and quantifying the relationships by developing analytical models can help design RMSs that can meet the needs of a changing marketplace while also enhancing sustainability performance.

Acknowledgements

We thank Prof. Yoram Koren from the Department of Mechanical Engineering at the University of Michigan who provided insight and expertise on Reconfigurable Manufacturing System that greatly assisted the research.

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