Roadmapping Towards Mature Collaborative Reconfigurable Manufacturing System

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Abstract. Reconfigurable Manufacturing System (RMS) has received a great deal of attention among researchers and industrial activists after being promoted by new manufacturing paradigms like Industry 4.0. Consequently, researchers are working on introducing a comprehensive, mature and collaborative framework of RMS. Still, there are several practical obstacles in the way of introducing collaborative RMS into corporates. Among these obstacles is a lack of knowledge about the status quo and strategic guides to realize new frameworks, especially when it is considering strategic decisions in a collaborative decision making (CDM) system. Thus, the main novelty of the present study is to gather and introduce 194 key performance indicators (KPIs) to give a general picture of the way of implementing newly developed collaborative RMSs. This framework covers four key axes in the RMS framework at the same time, including Servitization, Sustainability, Uncertainty, and Digitalization. Each axis is featured with several dimensions and for each dimension there are from two to 19 KPIs to monitor the implementation level. The KPIs have their own description and example of the formula. In addition, based on the PCDA cycle, the relationships between strategic objectives, KPIs, targets, and initiatives are given to connect the various parts of changing strategy.

Keywords: KPI; Reconfigurable Manufacturing System; collaborative decision making, Sustainability; Uncertainty; Servitization; digitalization

1 Introduction

Manufacturing firms in the current industrial environment have to deal with several deep changes that require increasing standard in products and designs and management of processes. The main factors that force the change from traditional manufacturing system to the Next Generation Manufacturing System (NGMSs) are dynamic market demand, high flexibility, CDM between different parts of the value network, quality products, growing customization, flexible batches, and short life cycle of products [1]. Over the years, the limitation of dedicated manufacturing systems (DMSs), cellular manufacturing systems (CMSs), and flexible manufacturing systems (FMSs) have become clear with adaptation to the newly emerged market features. For instance, DMSs make sure of production of the core products with a high production rate but with low flexibility. The features of products should remain unchanged during the lifetime of system and making changes is highly expensive and hard to make [2, 3]. Using FMSs, automated numerically controlled workstations can be connected using a suitable handling system from a central control unit. The key benefit of FMSs is higher flexibility for managing resources and produce a wide range of parts. Still, in many cases, the output of these system is less than DMSs and the equipment increase the final price of the parts [3]. Some of the drawbacks of these two systems were covered by CMSs, which are featured with using several independent working cells assigned to families of products that have identical processing requirements [4]. In spite of this advantage, CMSs are made to manufacture a specific number of products with a reliable demand level and adequately long lifecycle [5]. To overcome the limitation of the available systems, NGMSs combined high flexibility, reconfigurability, and artificial intelligence properties to meet the dynamic market demands [6]. Koren was the first one to introduce RMS in 1999. The NGMS are designed to make fast changes in structure, hardware, and software components possible and change production capacity and functionality rapidly within a part family to deal with rapid market changes or regulation changes [2].

The expected features of DMSs, FMS, RMs, CMSs and matured RMS are listed in Table 1. Clearly, RMSs is designed to contain the advantages of traditional manufacturing system along with flexibility and high throughput and matured RMS try to develop new aspects in the traditional RMSs.

Table 1. Comparison among the features of the existing manufacturing systems, based on [2, 7].

	DMS	**FMS**	**CMS**	**RMS**	**Matured RMS**
Cost per part	Low	Reasonable	Medium	Medium	Customised
Demand	Stable	Variable	Stable	Variable	Variable
Flexibility	No	General	General	Customised	Customised
Machine structure	Fixed	Fixed	Fixed	Changeable	Changeable
Product family formation	No	No	Yes	Yes	Yes
Productivity	Very high	Low	High	High	Productivity
System structure	Fixed	Changeable	Fixed	Changeable	Changeable
Variety	No	Wide	Wide	High	High
Uncertainty	No	No	No	somehow	Yes
Digitalization	No	No	No	No	Yes
Servitization	No	No	No	No	Yes
Sustainability	No	No	No	No	Yes

The RMSs are a new group of manufacturing systems with adjustable structure both in terms of hardware and software architecture [2, 8] and combine the following six main features [9, 10]: *Modularity*, *Integrability*, *Diagnosibility*, *Diagnosibility*, *Convertibility*, *Customisation* and *Scalability*.

There has been a growing trend of studies on RMS that cover a wide range of research questions[11]. Many of papers published in this filed are featured with introducing new methods to add some of the new features to available manufacturing systems [12], while providing methodologies for designing new RMS have not received the attention it merits.

Boucher et al. [7] introduced a matured collaborative RMS system and indicated that the technology is pretty mature on solutions to implement RMS; however, there is a relatively low level of adoption in the industry and for SMEs and CDM aspects in particular. To deal with these important points, the authors tried to take the main development in industry of the future into account along the recent years as a way to push the scientific production on RMS one the path forward. From this viewpoint, the latest gap analysis method is based on the main complementary issues of industry of the future and collaborative decision making between different decision makers in the network which are listed below:

- **Uncertainty management:** Managing different types of uncertainty can be the taken into account as the core of RMS. However, the industrial transition is pushing the limits of challenges and solutions to deal with uncertainty of production processes. **Digitalization:** Refers to using digital technologies to achieve new business models, revenues, and value-producing opportunities; it is the process toward a digital business.
- **Servitization:** By servitized organizations we refer to manufacturing/technology firms that provide services to their clients. Over the past decade, servitization has become a key strategy to keep competitive advantages for manufacturing organizations [13]
- **Sustainability:** To deal with the increasing concerns about sustainability, produces have been forced to introduce measures for examining sustainable manufacturing performance. These measures are aimed at integrating sustainability aspects.

In addition, creating tangible changes and potentials is a great challenge today. As to production system, we have to deal with several figures known as indicators [14]. These numbers reflect a general and compact picture of the process as a tool for assessment that provide the chance for a faster analysis [15]. For instance, current indicators are generally and only concentrated on the quality of product in time or may give the general effectiveness. Still, given the implementation of a fresh framework for a company, here we look for a comprehensive indicator bank that gives the strategic manager a chance to examine the current potential and determine diverse dimensions of the framework. In addition, it should enable them to examine the progress along with introducing changes. This paper is an attempt to give an introduction to the collaborative RMS indicator bank and the way these data are gathered. In addition, it showed the way such indicators connect the various elements in the change strategy.

Table 2. Keywords and investigated concepts to create the indicator bank.

NO	Axis	Keywords	No. of indica-tors	No. of papers	im-portant refer-ences
1	Uncertainty	Green, Sustainability, Sustaina-ble, Environmental, Waste, Re-source utilization, Emissions, Social, welfare +indicator or criteria or KPI	99	65	[19, 20]
2	Digitalization	Uncertain, Indeterminacy, predic-tion, Scalability, Diagnosability +indicator or criteria or KPI	60	41	[21, 22]
3	Servitization	Servitization, Tangible, Intangi-ble, Customer Service , Customi-zation +indicator or criteria or KPI	44	57	[8, 21, 23]
4	Sustainability (Environmental, Social. Cost factors)	Modularity, integrability, Con-vertibility, Technology, Products, Data, digitalization, digital +indicator or criteria or KPI	47	31	[24, 25]

2 Research Methodology

The criteria are key elements for planning and controlling a manufacturing process. They are more important for management and the main elements for selecting indicators. Through these evaluation, coordination, and control functions, purposes are used as a key instrument for management [16].

Given the fact that these indicators function as a tool for managers, general indicator structure is usually concentrated on financial or strategic matters. The ZVEI KPI system, the Profitability-Liquidity KPI system, and the DuPont System of Financial control are among the most common financial indicator systems [17]. In addition, the Balanced Score card relies on a framework to create key indicators about vision and strategy of a firm [18]. The Balanced Score Card is under consideration in this study as it implies that developing indicator systems is the same as creating an indicator bank through examining the related products.

It is important in the search approach phase to have a proper choice of the database to make sure the literature is of high quality and covers a large volume of documents found in the field of a required change in a firm. Afterwards, the phrases used to search and the information found in the publications are searched and filtered. For instance, as shown in the Section 3, the framework used in this study covers some key elements based on which we can achieve key concepts. Using the keywords in the definition for each challenge, the keywords that we can use in our search were extracted. For instance, in terms of sustainability, a search is performed in WoS using keywords such as "Emissions + indicator." The categories chosen to search based on the concepts and challenges explained in the Section 3 are listed in Table 2. In addition, the number of articles and the key references to create the indicators bank are listed. Figure 1 illustrates the strategy of gathering and selecting the bank of indicators. The PRISMA statement recommendations were used for information search including identifying papers for screening, eligibility, and included papers. The inclusion criteria were keywords on the title, abstract or keyword sections; published by scientific peer-reviewed journals, and published in WoS or Scopus. Papers published over the past seven years were more in focus (2015-2022).

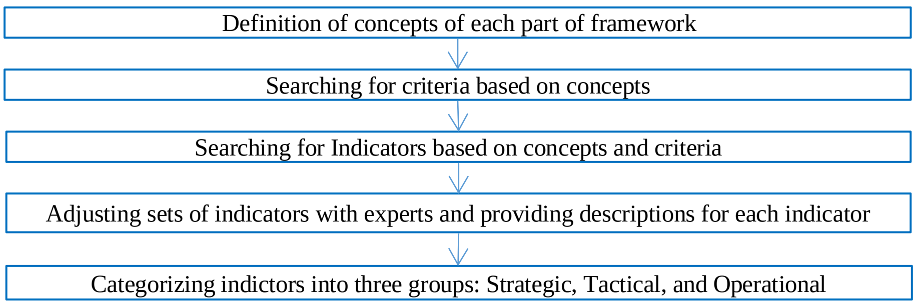

Fig. 1: Schematic representation of how the indicator bank is Prepared (Provided based on [26])

3 Resulting Monitoring System for collaborative RMS

The obtained indicator bank is designed to monitor mature RMS framework implementation in manfacturing companies that produce physical goods or offer services and products at the same time. It gives us four axes based on the framework, including sustainability, uncertainty, servitization, and digitalization, each with many dimensions.

Each dimension contains 2-19 KPIs to monitor the implementation status. One example of KPI and the pertinent operation KPI measure for each dimension in the axis 3 (Servitization) are listed in Table 3. All KPIs rely on quantitative scales that measure the implementation status of a collaborative RMS-concept in terms of percentage or degree. In general, 194 KPIs were introduced so that each had the same structure (Table 3). Each KPI contains a title, a description, detailing of the collaborative RMS-concept, an example to improve understanding, and the measurement-scale to examine levels of implementation.

4 Roadmap Toward Collaborative RMS

The relationship between the proposed framework and a performance measuring system is shown in Figure 2 namely indicators, targets, and initiatives. As mentioned in the Section 1, the proposed framework can be used in various organizations depending on the case and the level of their potentials. In addition, a company might need to alter its one or more framework dimensions depending on their challenges for making decision (see [7]). Thus, in the case of a systematic change inside an organization, we need a change strategy with clear dimensions and cause-and-effect relationship. Acceptable performance level is measured based on “targets” for the defined indicators. In addition, initiatives are developed to cover the gap of current and ideal states based on total budget, manpower, and other constraints.

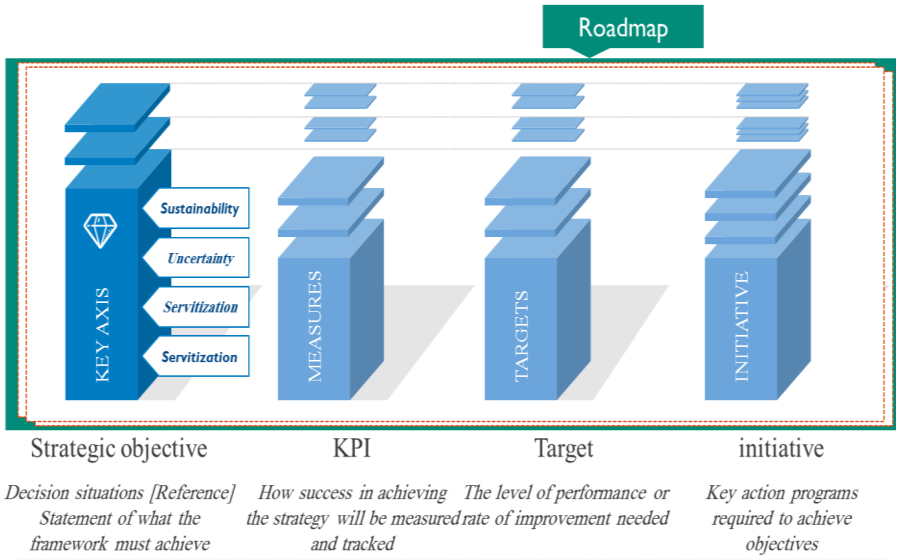

Fig. 2. Roadmap toward collaborative RMS.

Table 3. Maturity dimensions and assessment items for Axis 3 (Servitization).

Axis 3, Dimension 1: Customization (7 items)
Tool customization, Controller customization, Operation customization, System customization, Size customization, Colour customization, Design customization. **Example KPI**: Tool customization **Operational KPI measure:** [binary] Possibility to use same tools to assemble different variants.
Axis 3, Dimension 2: Tangible/Intangible Services (2 items)
Number of Service Types, Number of Services **Example KPI**: Number of Services **Operational KPI measure:** [number] of the of services offered by the company. The more services a company offers, the higher is the degree of servitization.
Axis 3, Dimension 3 – Revenue of Servitization (13 items)
Share of Direct revenue from Services, Share of Indirect revenue from Services, Share of Direct Costs from Services, Share of Indirect Costs from Services, Growth in sales, Growth in revenue, Growth in profit, Return on investment, Market share growth, Profit as a percentage of sales, Return on investment, Cost saving, Market share growth **Example KPI**: Share of Direct revenue from Services **Operational KPI measure:** [%] of annual revenue from directly selling services / total revenue from selling products and services
Axis 3, Dimension 4 – Customer Service (11 items)
Number of Customers Serviced, Product-Service (P-S) Continuum, Value Basis of Activity, Services Reputation, Alignment with customer's requirements, Bringing service to market quickly, Number of service evaluation, Service as the main reason customers selecting us, Customer retention rate, Customer satisfaction, Degree of loyalty **Example KPI**: Number of Customers Serviced **Operational KPI measure:** [number] of customers reached by the firm's services
Axis 3, Dimension 5 – Service orientation of the company (8 items)
Service orientation of corporate values, Service orientation of management behavior, Service orientation of employees behavior, Service orientation of employee recruitment, Service orientation of employee compensation, Service orientation of employee training **Example KPI**: Service orientation of employee training **Operational KPI measure:** [Degree] which refers to the extent to which service-related performance is evaluated and rewarded within the organization (Musser based on Likert scale)
Axis 3, Dimension 6 – Strategic intent for future service offering (6 items)
Strategic intent to develop a service breadth, Strategic intent to develop a service depth, Developing brand identification, Additional services to loyal customers, Constant learning from supplier/customer/competitors, Ability of service customization Supplement two new services in the next year **Example KPI**: Strategic intent to develop a service breadth **Operational KPI measure:** [%] number of supplement of new services in a year / the number of target
Axis 3, Dimension 7 – Logistics of Service (10 items)

Infrastructure for service delivery, Info Sys applied in service delivery, Inter-organisational info sharing, Number of services not finally delivered, On-time contract delivery, Time of service delivery, Number of errors in service delivery, Time between service order and service delivery, Percentage of use of service delivery capability, Delivered On time
Example KPI: Delivered On time
Operational KPI measure: [%] of orders delivered on time

Figure 3 illustrates the introduced performance measurement system. Incrementing the chance of independence between the component and process (workstation modularity)" is considered as a criterion in RMS dimension. Therefore, to track progress to achieve the target (i.e. the level of workstation modularity), it is covered as an indicator. As a result, to fill the gap between the current and preferred performance, an initiative is developed named "to change the workstation through redesigning the layout."

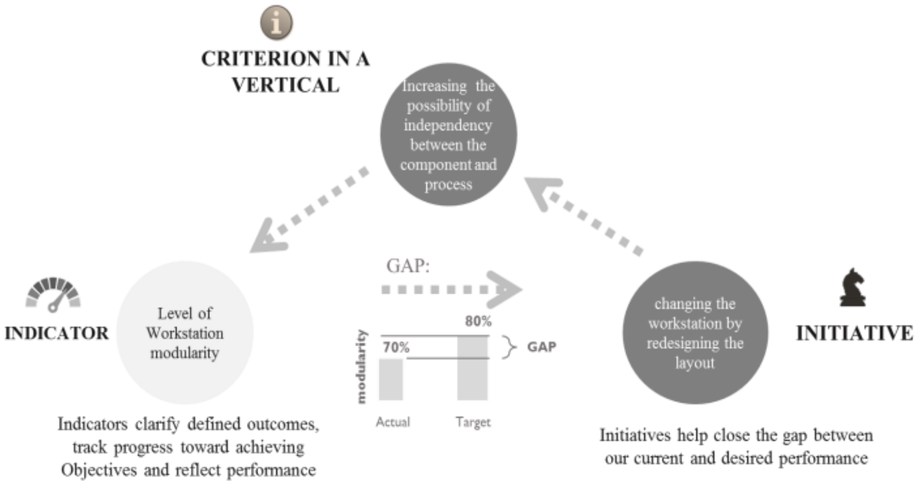

Fig. 3. An example of performance measurement system.

To have a complete description of how the roadmap will be practically applying the indicator bank, here we provide an example of developing servitization on HeiQ Materials AG, an international textile chemical company that produces advanced technologies for its customers. The senior managers of a company have to have a meticulous understanding of the service offerings in that specific industry benchmark companies and their competitors. Then they are able to assess if the number of offering services and their depth is sufficient or if there is a need to ameliorate. Moreover, the organization can make an assessment of the types of services in its current situation and rank them as basic, intermediate, or advanced. As an example, the HeiQ Materials Company has applied many services to develop value by collaborating with the clients. As a result of this, they have fitted service offerings to customers' specific demands and prolonged the depth of each service to fulfill customer needs. The organization's service portfolio shows a combination of base (technical support, troubleshooting, legal compliance services), intermediary (customer training, mill recommendations, environmental health safety, and sustainability support), and advanced services (usually internal to a customer, e.g. testing customers product, marketing support, ingredient branding). By going throw the depth in service approach, HeiQ extends the value in collaboration with its customers through its business offerings. Finally, in five years, this company has gained about a thirty percent compound annual growth rate in its sale [27].

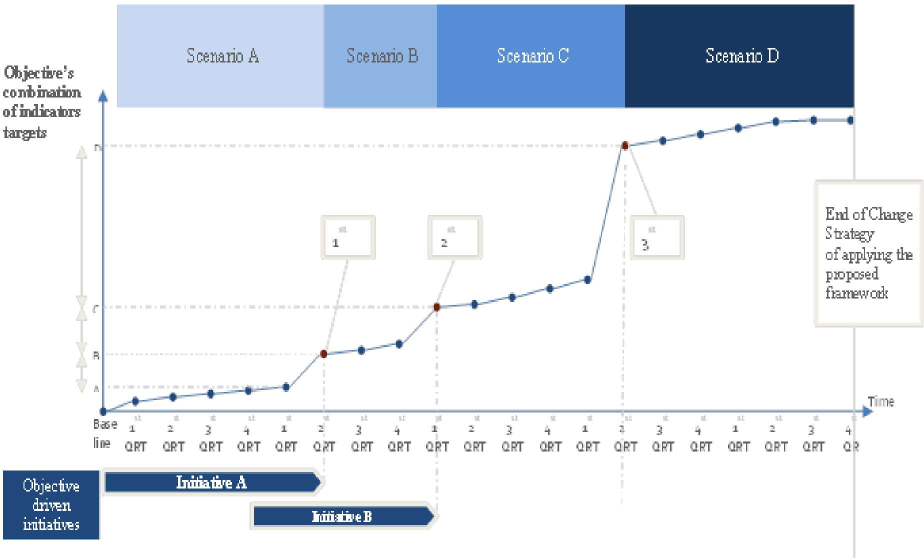

Fig. 4. Scenarios in measuring the performance of each concept

To complete the above description, four key scenarios are taken into account to have a comprehensive measure of progress for each goal.

- **Scenario A:** Objective measured using indicator Progress of Initiative A and other indicators that are not measurable currently.
- **Scenario B:** Objective measured using indicators of Progress of Initiative B.
- **Scenario C:** Objective measured through indicators not covered by the drive initiatives progress.
- **Scenario D:** Objectives measured using indicators, improving one or more indicators, targeting ambitious because of the effect of other driven objectives initiatives accomplishment.

These four scenarios in measuring the performance of each indicator of each concept of the proposed framework are illustrated in Figure 4.

5 Conclusion and Further Research

Industry 4.0 has created many manufacturing opportunities. One of the most important of these axes is RMS. Although most RMS models were focused on operational and production-level models in a factory, recently the attention of the researchers has been drawn to axis such as digitalization, Uncertainty, Servitization, Sustainability. Moreover, despite research on participatory RMS models, there is still a great need for progress measurement tools to control changes in organizations, machines, and value networks. One of the important measurement tools, which simultaneously causes the compatibility of different components of the value chain, is indicators. In this study, for the first time, based on components of mature collaborative RMSs, 194 indicators were collected, classified, and defined by a systematic search in the literature. With this indicator bank, the organization that wants to become a mature organization in the field of collaborative RMS can firstly measure its current status compared to the optimal state, and secondly, during the continuous improvement, it can measure its percentage of progress by dashboards prepared based on this indicator bank. Moreover, the paper tried to explain how to implement these indicators and introduce a practical roadmap through change management. Concisely, by this indicator bank, as well as the matured RMS model which was introduced in the paper, companies that wish to convert their manufacturing system to an RMS-based system can easily apply the selected indicators. Moreover, the paper subject that which roadmap to implement this system is efficient and user-friendly.

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