2018

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Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 21 (2018) 26–36

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

15th Global Conference on Sustainable Manufacturing

Sustainable Living Factories for Next Generation Manufacturing

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Abstract

To be profitable and to generate sustainable value for all stakeholders, next generation manufacturers must develop capabilities to rapidly and economically respond to changing market needs while at the same time minimizing adverse impacts on the environment and benefiting society. 6R-based (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacturing) sustainable manufacturing practices enable closed-loop and multi-life cycle material flow; they facilitate producing more sustainable products using manufacturing processes and systems that are more sustainable. Reconfigurable Manufacturing Systems (RMS) and its characteristics of scalability, convertibility, diagnosability, customization, modularity and integrability have emerged as a basis for living factories for next generation manufacturing that can significantly enhance the system sustainability by quickly adjusting system configuration and production processes to meet the market needs, and maintain the system values for generations of products. This paper examines the significance of developing such next generation manufacturing systems as the basis for futuristic sustainable living factories by adapting, integrating and implementing the RMS characteristics with the principles of sustainable manufacturing to achieve value creation for all stakeholders.

Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).

Keywords: Sustainable manufacturing, Reconfigurable Manufacturing Systems, Value Creation

1. Introduction

Sustainable future, characterized by continuously improved quality of human life in terms of happiness and prosperity, associated with food, shelter, sanitation, education, healthcare, job satisfaction, etc., is fast becoming a necessity while the global and local socio-economic and demographic conditions impose constraints for sustainable

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2351-9789
Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).
10.1016/j.promfg.2018.02.091

development which is most commonly defined by economy, environment and society.

Manufacturing has been the engine for wealth generation and societal wellbeing worldwide, thus leading to sustainable living with happiness and prosperity. Technological advances in manufacturing continue to play a crucial role in promoting economic growth and generating societal benefits for decades. Sustainable factories of the future are the basis for industrial growth and prosperity for economic, environmental and societal advancement. Visionary thoughts on designing and developing such factories of the future must also include the concept of living factory where the factory environment can continually be updated, adapted and reconfigured to suit the changing industrial needs and marketability of products to meet societal needs.

A sequence of unrelated global events —both political and technological— that all happened in just 10 years (from 1991 to 2001) initiated the current globalization era, and, in turn, triggered the creation of Reconfigurable Manufacturing Systems, and simultaneously deepened the global attention to sustainability.

During this decade of the 1990s the European Union was created (1992) and NAFTA was formed (1994). India was opened to foreign investments (1991), and China formally opened its borders to industrial investments (2001). In the same decade, the US manufacturing industry started to migrate abroad: Boeing R&D to Russia (1993), and the automotive industry first to Mexico (1994), and then to India (1995) and China (1997) [1].

Globalization has changed dramatically the consumption habits of society. Individual consumption of products grew dramatically during this period, and continues to grow rapidly, which prompted *sustainability* concerns. "In 1961 almost all countries in the world had more than enough capacity to meet their own demand; by 2005 the situation had changed radically with many countries able to meet their needs only by importing resources from other nations. Humanity's demand has more than doubled over these 45 years" [2]. The surge of globalization in the 1990s enabled nations to meet their needs only by importing resources. The growing demand for consumer products is satisfied using increasingly larger quantities of natural resources. Therefore, at the turn of the 21st Century, product and process sustainability turned out to be a major global concern, which requires innovative solutions.

Sustainable living factories are the future in manufacturing system development as they are technologically advanced, adaptively reconfigurable and are economically advantageous offering significant societal benefits. The capability to produce high volume, low variety products and low volume, high variety products would make such living factories truly versatile and novel.

This paper presents the foundational aspects of developing sustainable living factories of the future beginning with the historical development of Reconfigurable Manufacturing Systems (RMSs), followed by a description of deployable characteristic features of RMS and its architecture. A general outline of Sustainable Manufacturing (SM) and its application to RMS is then presented by showing the compounded benefits of marrying RMS with SM for greater productivity, performance and manufacturing quality for the factories of the future.

2. Reconfigurable Manufacturing System – A Living Factory

2.1. The Emergence of RMS

RMSs emerged in the automotive powertrain industry. Because of the high precision needed in powertrain components (about 10μm), the high-tech segment in automotive production is the powertrain industry that produces engines and transmissions for cars and trucks. There are about 100 powertrain plants in the U.S. and Canada, and these are the most expensive plants (by far more expensive than the automotive assembly plants).

Until the 1990s, most powertrain components were produced on dedicated machining lines (DMLs, often referred to as "transfer lines"). DMLs are designed to produce very large quantities of just one product, at a very high production speed, which yields high productivity. For example, engine blocks of cars are machined on a DML at a cycle time of 30 seconds (two engines per minute). The investment cost of DMLs is relatively low, because (a) the machines that constitute the line are designed to operate only at a fixed cycle of axial motions, and (b) multiple cutting tools can operate simultaneously on each machine, which enables achieving high productivity at low cost.

As long as a dedicated line operates at its planned capacity, it produces many parts at very attractive prices. But what happens when, for example, the price of gasoline is going down, and consumers are buying many General Motors' (GM) full-sized pickup trucks with V8 engines? In this case GM does not have enough V8 engines to produce enough full-sized pickup trucks to meet the demand. GM not only loses sales and profit, but also loses market share, and a sharp rebound in market share is usually not possible.

Note that for the same scenario, the DMLs that produce four cylinder engines (I4 or L4) stay partially idle. But workforce and maintenance costs are being fully paid. A report published in 1998 indicated that the average utilization of the surveyed DMLs in the European auto-industry in the mid-1990s was only 53% [3]. The U.S. auto industry was well aware of the limitations of DMLs. CNC machines were in little use in the auto industry since the 1970s [4]. In an industry-university workshop in 1992, replacing dedicated machines with CNCs in the powertrain industry was thoroughly discussed. The main limitation was the price of high-power, high-precision CNC machines which in 1990 was around $800,000. However, with the spread of globalization, the cost of such a CNC machines started to decrease substantially, and in 1998 it was around $300,000.

In 1995, in a proposal entitled "Engineering Research Center for Reconfigurable Manufacturing Systems" (ERC-RMS) that was submitted by the University of Michigan to the U.S. National Science Foundation (NSF), the Center Director, Yoram Koren, conceived the RMS architecture, principles and characteristics. The new Center was awarded $47 million by the NSF and private industries to develop the RMS paradigm. In this proposal the term Reconfigurable Manufacturing Systems was coined, and was defined as a manufacturing system that has "exactly the production resources needed, exactly when needed" [5].

Many of the 100 powertrain factories in the U.S. and Canada are designed and operated today according to the RMS principles and RMS architecture articulated to NSF in 1995, and possesses the RMS characteristics that were explained in the RMS keynote speech delivered in the 1999 CIRP General Assembly [6]. This keynote paper became the highest cited paper of CIRP, and opened a whole new area of global research on RMS.

In 1997 Ford Motor Co. decided to build in Windsor, Canada, its first powertrain production factory that will be based on CNCs, called by Ford "Flexible-Reconfigurable Manufacturing Factory." It was not easy to convince Ford management to approve the building of this factory because the initial investment cost would be higher than that of a factory based on transfer lines. The ERC-RMS played a critical role in persuading Ford management by developing an original Lifecycle Cost-Model that compares the economics of RMS versus transfer lines during 12 operating years. In his keynote speech at a CIRP-sponsored conference in 2005, Mr. Roman Krygier, Group Vice-President for Global Manufacturing and Quality, Ford Motor Company, acknowledged this contribution [7]:

"Modeling and analysis confirmed that flexible/reconfigurable manufacturing does not cost more than traditional manufacturing. This was confirmed by the ERC-RMS Lifecycle Cost Model software package. The ERC Lifecycle cost model was utilized during the simultaneous engineering phase for the 3V Valve program at the Ford Windsor Engine plant annex and it confirmed from a total cost standpoint that the flexible/reconfigurable manufacturing system designed by Ford (Figure 1) offers better investment and operational efficiency for initial programs (and second cycle changes) over the life of the product, or adding new products through the lifetime of the manufacturing system."

Mr. Krygier deserves the credit for being the first to make the connection between reconfigurable systems and sustainability. In his 2005 keynote speech Mr. Krygier said:

"With traditional dedicated manufacturing systems, an entire system has to be replaced by a new manufacturing system when we launch a new engine architecture. When implementing reconfigurable manufacturing systems, the system can be reconfigured for the new engines by reconfiguring hardware and software so that the values of the manufacturing system are maintained for generations of products. This approach enhances sustainability of manufacturing." [7].

Today, almost 20 years after opening the plant, the Ford Windsor Engine plant has gone through three reconfigurations in which machines were added or replaced, and is fully operational.

As manufacturing activities consume a large amount of resources and result in significant burden on the environment [8] and society, addressing the global challenges faced requires a competitive sustainable manufacturing approach to simultaneously consider the impacts of industrial activities on the economy, environment and society [9]. These three aspects are known as the three pillars for sustainability.

- **Economy** – RMS increase the manufacturing system value for the manufacturer, thereby making the business very profitable.
- **Environment** – Usually refers to reducing carbon footprint and water usage, but the main contribution of RMS is obtained by not scraping the old transfer lines every few years.
- **Society** – supplying high-quality products, exactly at the time that consumers need them.

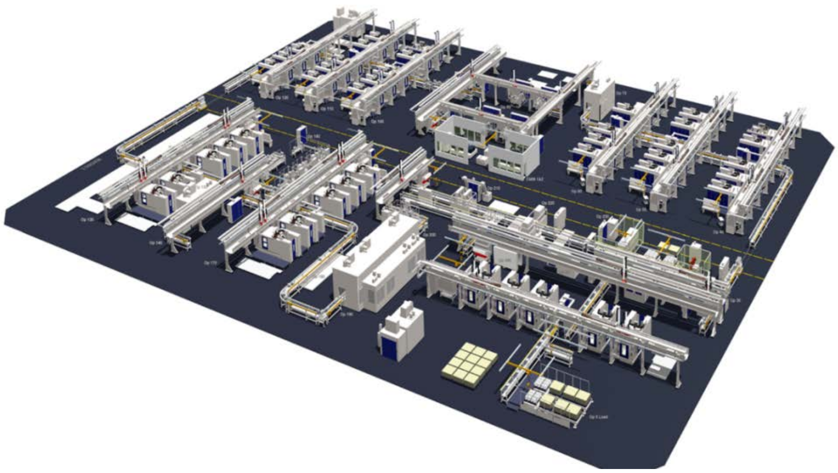

Figure 1: Schematics of the flexible/reconfigurable manufacturing system at Ford Windsor Plant [7]

A systematic methodology for designing RMS architecture has been developed [10]. The RMS architecture enables manufacturers to respond rapidly to changing market needs while concurrently minimizing adverse impacts on the environment and society [11 – 13]. Thereby, RMS satisfies the three pillars of sustainability.

This paper explains how the RMSs can create sustainable value for all stakeholders, while addressing competing market forces. An overview and definition of the 6R-based approaches for sustainable manufacturing is presented to highlight how it can enable increasing economic benefits while minimizing negative impacts on the environment and society.

2.2. The Characteristics of RMS

In the previous century high volume manufacturers relied mainly on dedicated manufacturing lines that produced low cost products. Flexible manufacturing systems that offer volume/mix flexibility could be rarely found. However, the challenges raised by globalization required achieving jointly the objectives of both low cost and volume/mix flexibility.

In response to this challenge, RMSs were introduced at the turn of the 21st Century. RMSs are designed in order to improve the system responsiveness to rapid market changes. RMSs allow changing the system structure and its resources rapidly and cost-effectively, in order to possess “exactly the capacity and functionality needed, exactly when needed” [5].

Globalization has resulted in (a) an increased frequency at which new products with shorter lifecycles are introduced, and (b) a higher demand for more customized products. These conditions create dynamic markets in which manufacturers can improve their competitiveness only by quickly and cost-effectively responding to changing customer needs.

The manufacturing engineering solution to respond to changing markets is implementing manufacturing systems that are able to quickly change their production capacity and their functionality in a cost-effective manner. The role of RMS characteristics as drivers for value creation through system scalability that promotes sustainability has been introduced [14], but requires further elaboration that is offered here.

RMSs possess six core characteristics: Scalability for capacity planning strategies [15 – 17], convertibility for economic switching of products [18], diagnosability that enables in-process product inspection [19], as well as customization, modularity, and integrability – characteristics that enable designing cost-effective RMS. Interpretations to these characteristics are summarized in Table 1.

These six RMS characteristics are widely used in the design of (a) reconfigurable machine tools [20], (b) machining systems [21, 22] and assembly systems [23, 24], as well as (c) supply chains. The agility and speed of maintenance may play a significant role in the system design [25 – 28], as well as the corporate culture [29].

Table 1: Core characteristics of RMS [10]

Characteristic	Interpretation
Scalability (Design for capacity changes)	The capability of modifying production capacity by adding or removing resources and/or changing system components
Convertibility (Design for functionality changes)	The capability of transforming the functionality of existing systems and machines to fit new production requirements
Diagnosability (Design for easy diagnostics)	The capability of real-time monitoring the product quality, and rapidly diagnosing the root-causes of product defects
Customization (Flexibility limited to part family)	System or machine flexibility around a part family, obtaining thereby customized flexibility within the part family
Modularity (Modular components)	The compartmentalization of operational functions into units that can be manipulated between alternative production schemes
Integrability (Interfaces for rapid integration)	The capability of integrating modules rapidly and precisely by hardware and software interfaces

2.3. RMS Architecture for High-volume Manufacturing

Figure 2 shows the typical RMS architecture for high volume manufacturing (such as the one implemented at the Ford Windsor plant) [30]. The system contains multiple stages; at each stage, there are multiple parallel machines that are integrated into the system by using overhead gantries. All machines in each stage are identical, and perform identical operations. Each gantry has two grippers: The first to unload the finished part from a machine, and the second to load a new part to be processed by the machine. The machine can be either a CNC machine (in most industry plants), or a reconfigurable machine tool (RMT). Note the planned reserved spaces that enable the option of adding machines to increase capacity very rapidly.

At the system level, each machine is a module, and its function can be converted when a new type of part is required to be manufactured by the system. Furthermore, all the stages in the system are integrated into one large system by a long overhead gantry, or a conveyor (Figure 2) that transports parts between the stages. Adding machines to the stages and extending the gantry to serve the new machines achieve scalability, which enlarges the system capacity (to increase the system throughput). A typical RMS possesses the characteristic of diagnosability that is accomplished by including in-line inspection stations that are located next to critical machining stations. Moreover, to process a certain part family, Reconfigurable Machine Tools may be installed, thereby implementing the customization characteristic, too

The RMS characteristics not only lead to rapid system responsiveness at low cost, but they can also contribute to achieving system sustainability.

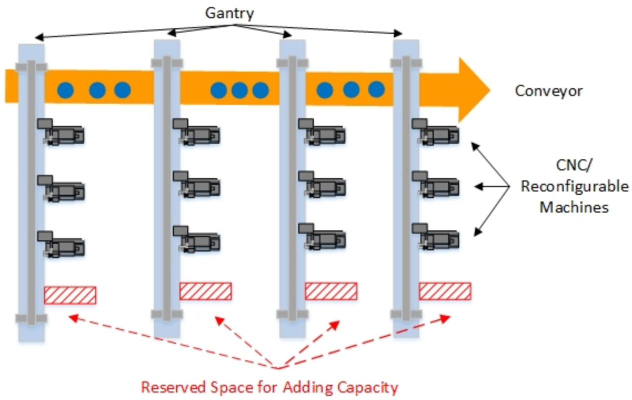

Figure 2: A typical RMS architecture

3. System Architecture for Individualized Product Manufacturing

The foresight for creating personalized, or individualized products using RMS was introduced in 2006 in a patent application [31], and details and examples were presented in scientific papers [32 – 34]. However, these papers have not elaborated on the manufacturing system that can cost-effectively produce individual products. Here we propose how to modify the RMS traditional architecture such that it can be implemented for the production of individualized products.

The proposed architecture enhances the resilience of the manufacturing system, and may realize our vision of “market-of-one products at affordable cost”, which would tremendously enhance product sustainability, since the buyer receives exactly what s/he needs. Design and manufacture of such market-driven products would also promote “sustainable” products and processes to enable long-term benefits to all stakeholders while preserving the eco-balance in the natural environmental system offering economic and societal benefits.

Figure 3 shows our futuristic RMS for individualized production. It is designed according to the RMS principles and RMS characteristics. Different from a traditional RMS for mass-production, here the machines at every stage may not be necessarily identical. That means that the equipment is of the same type, but it may be scaled or reconfigured to fit markets and product variants. New technologies – such as additive manufacturing (Stage B) and human-robot collaborative assembly (Stage D) – may be integrated into this RMS. For example, since additive manufacturing is a relatively slow operation compared to other operations in the system, more machines are needed in Stage B, and building the part on each machine may take a different time.

In individualized production, different product variants may have different process sequences, because of: (a) different task constraints, and (b) the requirement to improve the machine utilization and system throughput. Therefore, the RMS for individualized production should be designed with more flexible product routing than a traditional RMS that is designed for mass production of a single product. Adding a return conveyor (or a gantry) enhances significantly the processing sequence options. In Figure 3, four product variants are simultaneously produced in the system (shown with four colors). Products II, III and IV move forward through the system, while Product I goes back to machine A2 through the return conveyor, after it is processed by C3; the reason for this route may be either due to a constraint of task precedence (e.g., the task on C1 should proceed that on A4 and C4), or the reason that A2 is initially unavailable.

Because of the different processing times of the operations (e.g., the operations in Stage D that involve people) and the large number of possible process sequences, line balancing is a very challenging task in this production system [35]. Moreover, a sophisticated part routing system based on adaptive control that changes the processing speed during production [36, 37] as well as cross-coupled principles [38, 39] that coordinate the speed of operations in two (or more) machines to obtain system optimization should be developed. Having the return conveyor and sophisticated software for optimal part routing, enable moving parts to be processed in the system at any order, thereby optimizing the system utilization, which further reduces product cost.

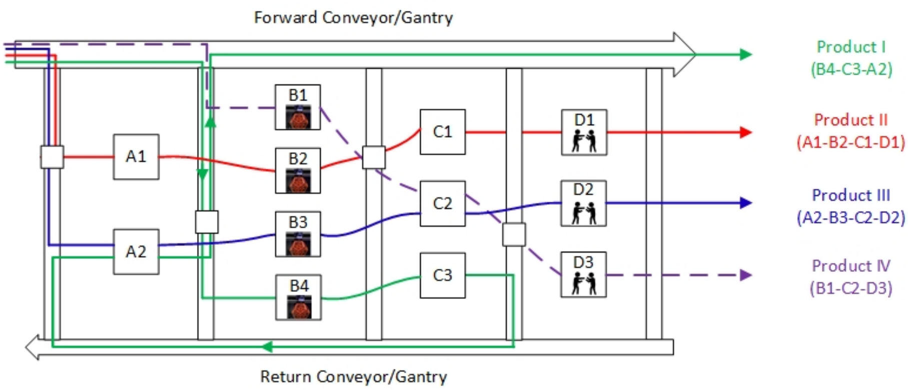

Figure 3: RMS for individualized production

4. Sustainable Manufacturing

Responding to the challenges that socio-economic and demographic conditions impose in the 21st Century, it becomes imperative that manufacturing systems should be designed for sustainability.

4.1. Sustainability for Manufacturing Innovation

Sustainability as the driver for innovation: Numerous studies and in-depth analyses of sustainability concepts and applications have shown that sustainability is a driver for innovation. The most notable among these studies include an early work published in the Harvard Business Review [40].

Innovation promotes accelerated growth in manufacturing: It is well-known that innovation in industrial production with advancement of product and process technologies leads to technological advances with competitive advantage, and this promotes accelerated growth in manufacturing. Sustainable products and processes are known to be innovative, and they contribute to societal and environmental benefits, too.

Manufacturing is the engine for wealth generation and societal well-being: National economy of any country heavily depends on the manufacturing capacity and the diversity of products and processes developed for its population, and for marketing to other nations. Developed and developing nations have shown the pivotal role of manufacturing in job creation, societal well-being and national economic advancement.

4.2. Sustainable Manufacturing: Definitions

There are numerous definitions and descriptions for sustainable manufacturing (US Department of Commerce, 2009; NACFAM, 2009; NIST, 2010; ASME, 2011; NSF, 2013; ASME, 2013). However, almost all such definitions fall short of showing the connectivity among the above integral elements, particularly connecting sustainability with innovation and value creation.

Sustainable manufacturing deals with three integral elements: *products, processes and systems.* To achieve sustainable production, each of these three integral elements is expected to demonstrate: (a) reduced negative environmental impact; (b) offer improved energy and resource efficiency; (c) generate minimum quantity of wastes; (d) provide operational safety; and offer improved personal health, while maintaining and/or improving the product and process quality [41].

4.3. Product and Process Innovation for Sustainable Manufacturing

Developing innovative products, processes and systems is a significant aspect of sustainable manufacturing, and it involves a holistic approach to manufacturing different from the traditional manufacturing practices where the quality and performance characteristics are measured and quantified independently, often with no consideration of the effects of other integral elements. The emerging holistic and integrated approach requires all stakeholders to work together on common objectives with total commitment. To enable innovation in sustainable manufacturing, innovation must be embraced at the product, process and systems levels with close interactions among each other [42]. System innovation can be built on the foundation of product and process innovation.

4.4. Sustainability Elements at Product and Process Levels

Since there are multiple streams of energy, materials/resources and waste/emission involved at different stages over a product's life, the total life-cycle must be considered in order to evaluate a product's sustainability score for comparison between different designs, or between different production strategies. Graedel [43] presented an extensive study of streamlined life-cycle analysis (SLCA) methods, including matrix approaches using target plots, and considering five major product life-cycle stages: pre-manufacture; manufacture; product delivery; use; and recycling. Subsequently, a simplified total life-cycle of a product was introduced including four key life-cycle stages – pre-manufacturing, manufacturing, use and post-use [44]. To achieve multiple product life-cycles with the goal of near-perpetual product/material life, it was shown that design and manufacturing practices for next-generation products must consider these product life-cycle stages using a more innovative 6R approach (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture) with transformation from lean to green to sustainable manufacturing [45]. A comprehensive systems approach can then be developed to cover products, processes and systems to enable sustainable value creation.

5. Evaluation of System Sustainability based on 6R Methodology

The RMS characteristics not only lead to rapid system responsiveness at low cost, but they can also contribute to achieving system sustainability. The scope of the system used in manufacturing can vary from the production line to the plant/factory, to the enterprise, and beyond, to cover the entire supply chain. In order to manufacture sustainable products using sustainable manufacturing processes, the systems used must possess capabilities that will help improve economic, environmental and societal sustainability. A framework to develop metrics for evaluating system effectiveness in delivering these capabilities is shown in Figure 4 [46].

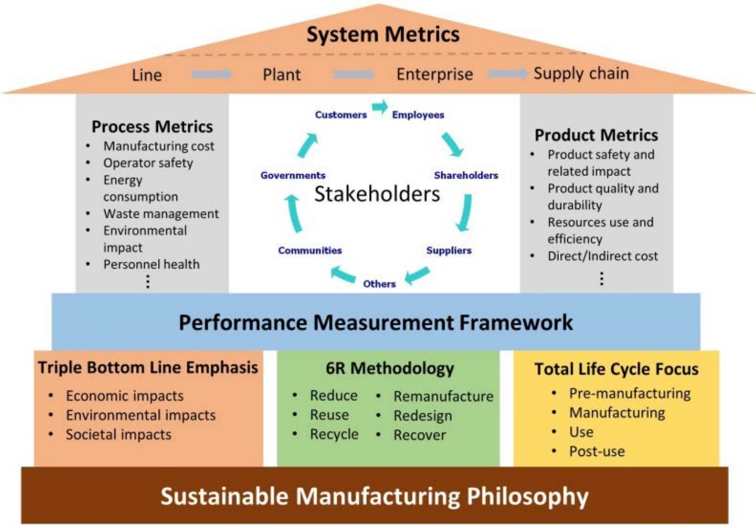

Figure 4: Sustainable manufacturing performance measurement house [46].

The framework, established emulating the 'Toyota House' used to represent the principles in the Toyota Production System [47], visually organizes all criteria relevant for system sustainability evaluation. As illustrated, both product sustainability metrics and process sustainability metrics (two main pillars in the house) must be integrated for the system level evaluation, by considering impact on all stakeholders, both internal and external. This framework can be used to identify metrics and aggregate those to assess system sustainability performance, following an approach similar to that described previously for *ProdSI* and *ProcSI* [48, 49]. For example, Figure 5 shows clusters and sub-cluster relevant when evaluating plant/factory sustainability performance. Metrics suitable to assess each of these aspects (details in [46]) can be normalized, weighted and aggregated to determine a Plant Sustainability Index (*PlaSI*). Similar indices, based on comprehensive metrics, can be developed to evaluate production line sustainability (Production Line Sustainability Index – *PlaSI*) and enterprise sustainability (Enterprise Sustainability Index – *EnSI*).

RMS can influence many aspects that drive sustainability performance of manufacturing systems. RMS characteristics can also enhance the capability to implement various 'R's to achieve more sustainable manufacturing. For example, modular machine tools and systems (modularity) in RMS allow mobilizing and combining capabilities optimally, as needed. This avoids having under-utilized and idling resources that continuously consume resources, generate wastes and emissions leading to adverse environmental impacts. For example, modularity in RMS can reduce energy consumption for production, transportation, maintenance, etc., to improve plant/factory sustainability due to efficient material and energy usage. Modularity can enable quicker system reorganization for manufacturing and remanufacturing (Remanufacture) functions, as needed, and help reduce (Reduce) overall resource consumption. All this will help further facilitate enhancing TBL performance for more sustainable manufacturing.

Sub-Index	Cluster	Sub-cluster	Sub-Index	Cluster	Sub-cluster
Economy	Manufacturing Cost	Direct cost	Environment	Material Use and Efficiency	Material Content
		Indirect cost			Material efficiency and compliance
	Operational Performance	Operational efficiency		Energy Use and Efficiency	Energy content
Society	Health and Safety	Employee health and safety			Energy efficiency
	Stakeholder Engagement	Employee diversity and development		Other Resources Use and Efficiency	Water content
		Other stakeholders diversity and development			Water efficiency
				Waste and Emissions	Waste
					Emissions
				Product	Product EOL

Figure 5: Clusters and sub-clusters for plant sustainability evaluation (based on [46]).

Better convertibility can influence system sustainability in numerous forms. Machine, system configuration and material handling convertibility increase as the convertibility characteristics of those domains increase. When these aspects can be changed without much difficulty or delay, they permit consuming fewer resources more efficiently. Features such as better software and hardware interfaces, shorter configuration change times, number of alternate machine functionalities enabled through reconfigurable tools, etc., make a system more convertible and, therefore, can enable reorganizing and redesigning (Redesign) systems. In addition to ease of switching from component manufacturing to remanufacturing (Remanufacture), higher convertibility could potentially also enable reconfiguring systems to produce components from virgin and secondary feedstocks, thereby increasing capability of the system to recycle materials. On the other hand, when a system has higher scalability, throughput gains in smaller increments are feasible permitting more optimal capacity enhancement, avoiding idle/excess capacity and wastage of human, material and other resources. All this can help significantly lower resource consumption in manufacturing systems, leading to better environmental sustainability. Similar system level sustainability benefits can be derived by incorporating other characteristics of RMS in a manufacturing system to enhance its sustainability performance.

6. Conclusions

RMS characteristics influence manufacturing process and system performance as they enable optimally and flexibly adding capacity to meet dynamically changing customer requirements. Due to benefits in cost reduction, improved flexibility, better quality and related aspects, RMS characteristics will be direct enablers in enhancing economic sustainability performance at product, process and systems levels. Similarly, it is also possible to demonstrate that environmental and societal sustainability improvements are feasible through the implementation of RMS.

The rapid commercialization of additive manufacturing enables cost-effective production of individualized products. We present how additive manufacturing can be integrated into the RMS architecture to form the next generation manufacturing paradigm that enables cost-effective production of Market-of-One products, while maintaining sustainable manufacturing practices.

However, further research is necessary to extensively study and quantify both positive, and any potential, negative impacts of RMS characteristics on 6Rs and environmental and societal performance. Quantitative assessment of impacts will enable identifying ideal levels of RMS characteristic implementation. Analytical models to optimize RMS implementation to maximize product, process and system level sustainable manufacturing performance are also necessary. Integrating RMS and 6R-based sustainable manufacturing systems can provide the basis for sustainable living factories of the future to meet the needs of dynamic markets rapidly and economically while also ensuring environmental and societal wellbeing.

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