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Sustainable Manufacturing – Architecture for Manufacturing System

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ABSTRACT

While research in Sustainable Manufacturing has tremendously been extended along numerous dimensions; it has sparked new needs and requirements for industrial and research community. This research has proposed and elaborated the architecture for Manufacturing System of a firm in relation to sustainability in manufacturing. Architecture is proposed as a set of five interdependent elements: 'Context', 'Purpose', 'Function', 'Structure', and 'Process'. These elements have been conceptualized, in a wider context, from the perspective of larger containing systems (Enterprise, economic system, social system, and ecosystem). On this concept, essential content under each element has been framed keeping in view the salient requirements pertinent to Sustainable Manufacturing and the enterprise. Sustainability aspects relevant to a manufacturing firm are discussed alongside, in particular, from the perspective of emerging paradigm of Circular Economy. Architecture proposition is guided by research in Systems Thinking, Sustainable Manufacturing, and Manufacturing System. The research would serve as a guideline for manufacturing businesses towards systemic development and operation of a manufacturing system in view of environmentally conscious and economically sound manufacturing.

1. Introduction

Industrial activities involved in realization of products, including a variety of services in the manufacturing chain, consume considerable amount of resources and produce waste thus affecting the environment and society [1]. The level and pattern of activities, at both industrial and societal scale, are responsible to assure a desirable future. Last three decades have evidenced a growing concern on the protection of environment and eco-system. The concept of sustainability, originated within the notion of sustainable development, has gained an increasing worldwide acceptance in pursuit of improving the quality of life and well-being for the present and future generations [2]. Behind this notion is the fundamental insight of ecology that every product is produced and used in an inter-connected world [3]. Since the earlier prominence of a quest for sustainable environment, the concept has largely evolved after the idea of 3BL triple bottom line that includes social and economic impact of activities in addition to environment [2, 4].

Sustainability in manufacturing has become one of the most important issues to address, for pursuing the big picture of sustainable development. Today, people are very conscious to the deterioration of global environment and predictable shortage of natural resources in near future. Industry is considering seriously the recovery and reuse of used products in response to environmental regulations and societal pressure. Effective and efficient utilization of energy and material has become an essential requirement [2]. Manufacturers thus need to pursue activities which help in minimizing environmental impact while maintaining of social and economic benefits. Moreover, manufacturing companies need to change their worldview of a Manufacturing System, to accommodate new needs of sustainability [1].

A Manufacturing System (MS) is an integrated and inter-connected set of value chain structure, technology, processes, equipment, material and information flow, and control system. In relation to Sustainable Manufacturing (SM), the traditional system boundaries have largely extended to take the form of a sustainable supply chain system [5]. At the level of enterprise, as shown in Fig. 1, it integrates all upstream (procurement) and downstream (production, logistics, reverse logistics) processes, and links

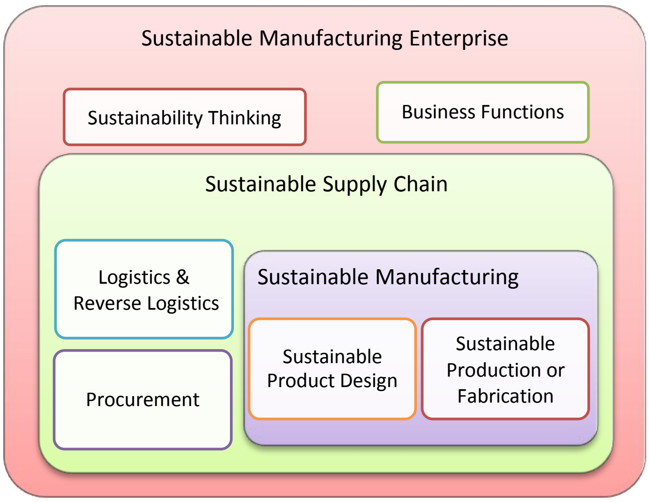

Fig. 1: Extended view of a sustainable manufacturing system.

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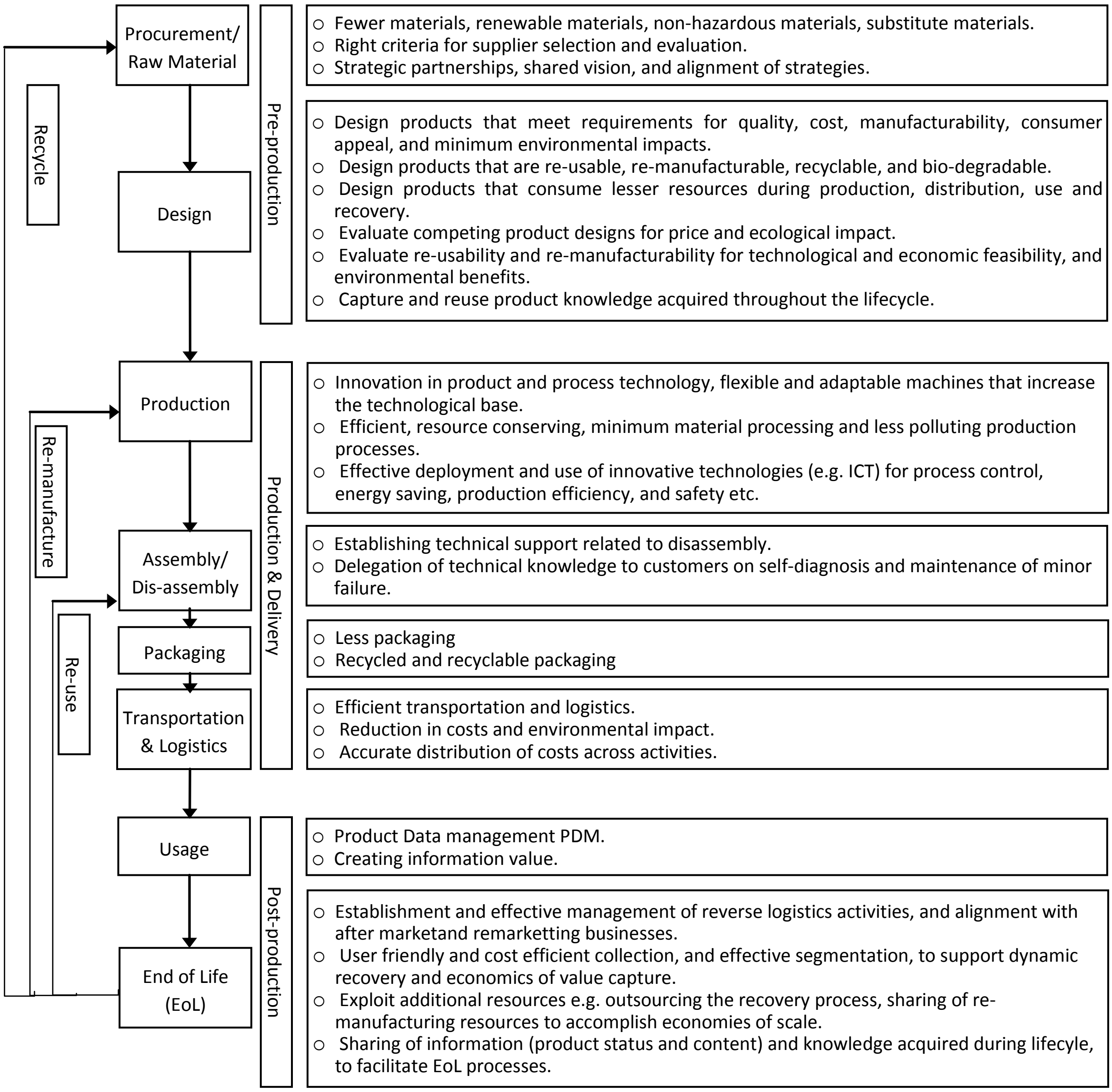

Fig. 2: Sustainable product lifecycle.

manufacturing and business functions effectively, to deliver sustainable value to all stakeholders and stay competitive. In this holistic view, the forward and reverse logistics need to be managed in a coordinated way [6]. However, addressing environmental concerns and resource efficiency at this scale is a challenging task, in particular, from the perspective of low cost operations. The firm's overall MS thus need to maximize the value (Environmental, economic, stakeholders) by dynamically recovering added value from different types and volumes of products and materials at their End of Life (EoL).

The scope of MS spans across all the Product Lifecycle (PLC) stages, simplistically divided into three segments with salient requirements against each, as shown in Fig. 2. 'Re-manufacturing' and 'Reuse' are new value adding processes that can leverage the design and production processes to create added value. The overall system, however, becomes large and complicated due to the dynamics of such an manufacturing environment, and management of additional interfaces pertinent to SM (e.g. After market, core recovery and recycling businesses etc.).

SM is a complex system involving interaction of multiple factors in three dimensions: economic, environmental and social. To address the complexity systemically, Systems Thinking (ST) is finding an increased attention from the research community. ST promotes holism and formulates complex problems as a system of interconnected set of problems for better understanding the behavior of a system [7]. The problem-solving methodologies [8] therein are vigorous to uncover a viable solution to the complex issues e.g. SM system.

Alongside, new manufacturing and economic paradigms are finding their way to take the charge. Cradle to Cradle (C2C) design and Circular Economy (CE) are relatively newer manufacturing and economic paradigms respectively which, supposedly, are going to transform (from minimal impact agenda to a positive impact) the traditional manufacturing paradigm that primarily focuses on increased efficiency of manufacturing processes and technological improvements. These paradigms, in their concept and protocol, produce products in a closed loop cycle over multiple life cycles thereby substantially reducing material and energy use, and leaving a positive impact on environment and economy.

Manufacturing systems are well known but there is a rare research on architecture framework or formalized description of an MS in relation to SM. Simplistic yet specific to the issue (e.g. SM) frameworks are needed which could facilitate holistic understanding and systemic development. Development may start with system concept or worldview that would be transformed into system architecture. The architecture framework is a formalized description of a system (e.g. enterprise system, manufacturing system), 'as a whole,' it's laid down functions and structural elements, its properties and behavior etc. A holistic view would improve understanding and interaction of its elements to the external context, strategy and operations, organization, and technology etc. for this whole to be a cohesive concept [9-12]. An MS as devised in this research, comprises five elements: 'Context', 'Purpose', 'Structure', 'Function', 'Process'. These elements need to be understood from different perspectives, in particular, sustainability, enterprise, and ST, to create a holistic picture of this system; one that can be utilized to improve the systemic interaction. An MS, however, can no longer be restrained into a fixed form or function(s). Once designed and in place, it must attain capability to not only remain responsive to changing needs but redefine, consequently, its function(s), structural elements, processes, and nature of interaction among them.

2. Sustainability in Manufacturing

Sustainability is a quality manifested in meanings of preserving, keeping and maintaining something. The idea for a sustainable world became popular with WCED's report in 1987 [13] that defined sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their needs. Later, the idea evolved with triple bottom line 3BL concept that broadened the scope from mere an environment oriented to a new definition involving three dimensions: environment, society and economy. In system's view, the natural resources contained by environment are delivered as eco-system goods (water, minerals, bio-mass) and services (air, land, and well-being) to industrial systems and society. Collectively this productive capacity is termed as 'natural capital'. Industrial systems, by utilizing environmental resources, fulfill societal needs in terms of providing products and services which have been added with economic value through industrial operations. This productive capacity is termed as 'economic capital'. Societal systems consume products, services, energy, and in return deliver value to industry by providing essential skills and market stability. While industrial and societal systems deposit wastes into the environment, they yet can create environmental value by protecting and restoring the environment. In sum, to protect all the three capitals a continuous quest towards sustainability needs to be pursued globally. With this in place, it seriously calls into question our current production, consumption and behavioral patterns.

A manufacturing enterprise is a component of socio-economic system. It produces parts and products as value added elements which may be used by other enterprises to produce goods that carry even more added value. A SM enterprise is one that has a system to: constrain and measure resource consumption and waste generation, produce sustainable value products, and contribute towards economic, environmental and social benefits. The products or product systems are component of enterprise system [14]. Products are expected to meet the needs of stakeholders and add value to the business, society and environment. Enterprises today extend to include all associated entities who, directly or indirectly, formally or informally, collaborate in all processes from initial product concept to its delivery to end users.

SM is about balancing value (benefits) for ecological systems, social systems and economic systems by deploying organizational competence and other value creation factors towards an effective and efficient utilization of material and energy. At the minimum, a Sustainable Manufacturing System (SMS) need to conserve resources, minimize environmental and social impact and measure sustainability performance. Product design and manufacturing process is the key to produce sustainable products. Integration of the two can bring functionally superior products to the markets that consume lesser resources during production and use cycles.

Sustainability problems are highly complex and contested, designated as wicked problems. These problems represent a methodological challenge attributed to a number of factors: cognitive difficulty and limitedness of resources in relation to problem resolution, multiplicity of interactions and high degree of interdependence and dynamics among parts of a system, value conflicts due to their diversity and lack of common understanding, increased breadth and depth of the issue embodied across multiple dimensions and domains, and connectedness and co-dependence of firms with other players in the entire network [15]. In addition, there is an ever increasing uncertainty, change, and inter-connectedness of problems posed on account of changing business environment. Off the shelf quick-fix and apparently simple, one best solution techniques, are seldom sufficient and adequate. In this complex and diverse milieu, there is a need of looking into the problem creatively and holistically i.e. taking an entire account of parts of a problem situation in different ways from different perspectives thereby avoiding sub-optimization [16, 17]. Hence, "The time has come for a Systems Thinking" says Fiksel [18].

ST looks at the whole in relation to its context, maintains relationships rather than unrelated objects, and highlights patterns rather than the contents of a system [19]. ST promotes holistic understanding, formulates complex problems, discerns interactions among multiple factors within a system, and gets a complete picture of the whole [7]. Holism induces capacity to systemically inquire the structure, processes and function of a whole in context of environment, to provide theoretical awareness and basis for criticism [16, 20]. System's analytical methodologies can be used to deal with and collectively analyze complex systems e.g. SMS, across different domains (society, environment, economy, etc.) and across different scales (local to global). ST offers a framework of different approaches and tools in relation to sustainability problems [21]. Sustainability in manufacturing, viewed as a system property, implies analysis and creation of sustainable value from the perspective of larger containing systems and multiple stakeholders therein [22].

Manufacturing businesses have met with a new set of constraints and problems that emerged during the past decade. Apart from growing environmental concerns, major problems faced are rapidly depleting natural resources (provided by eco-system), increasing price and volatility of raw materials and commodities. Businesses and society are in search of better industrial models that promise sustainable economic development in this milieu. CE aims at reducing both input of virgin materials and output of wastes by closing economic and ecological loops of resource flows thereby facilitating sustainable economic development. Potential business and competitive opportunities underpinning the CE concepts have stirred up a new interest in manufacturing sector and research community. The concept of circularity calls for innovation in industrial systems to create economical value while ecological and social benefits are additional value proposition [23]. Value creation in these manufacturing models is based on recovering the economic value retained in products at their EoL and offering like new (reused and re-manufactured) products [24]. Successful transition to CE requires technological and information management capabilities across entire product lifecycle, innovative concepts in product design , new material recovery methods, reverse logistics support, and culture adaptation [25]. Recent trends are encouraging in terms of adoption of cleaner production patterns, improvement in waste management process, an increased producer and consumer awareness, use of renewable technologies and materials, and adoption of suitable policies and tools [26-28].

The engine of the CE is C2C thinking [26]. A C2C manufacturing strategy aims at designing ecologically intelligent products and processes, on the laws of nature, that leave benefitting ecological footprint thus giving way to sustainable commerce. Guided by 12 Principles of Green Engineering, it identifies three key tenets in the intelligence of natural systems: waste equals food, rely on current solar income, and celebrate diversity. Rather meeting end of pipe liabilities, it shifts accountability to the design process and replaces traditional product design and development with a design that carries along positive effects to satisfy a multiplicity of economic, ecological and social questions [3]. In contrast to eco-efficient design solutions, focused on reducing resource consumption and associated impact, a C2C framework redefines the problem to address the source. In other words the process begins by analyzing the chemistry of materials to ensure that material is nonhazardous and a useful nutrient for subsequent generations after it has gone through its useful life. Scientific material assessment is governed by McDonough Braungart Design Chemistry (MBDC) protocol. The technical metabolism so designed, mirroring the biological metabolism, is a closed-loop MS in which benign, valuable, high-tech synthetic and mineral resources circulate in cycles: production, use, recovery and remanufacture. These systems run on renewable rather depleting energy and materials. Materials are selected as either biological nutrients or technical nutrients [29]. A C2C design of industrial systems has the potential to serve as a conceptual and technical platform to operationalize and accelerate the concept of circular manufacturing systems [27].

Technology has to play a vital role in realizing the concept of sustainability by providing means to fulfill the social and economical needs yet under environmental constraints [2]. For the SM sector, in particular, technology is fundamental enabling component for new business- and circular manufacturing models [30]. Technological capabilities need to be compatible with the requirements of processes and operations so that products of relatively more value are produced with lesser costs and undesirable impact. Core technologies, resting on a strong base of knowhow, can create competitive advantage in form of designing, developing and producing a variety of eco-friendly products. However, it requires broader planning vision and ability to use same knowledge in different contexts. Furthermore, emerging technologies e.g. information and communication technology (ICT), Internet of Things (IoT), Cyber-Physical Systems (CPS) etc. may be integrated and synchronized from business perspective, to support new ways of working that could lead to radical innovations. Notwithstanding, firms will come up with same non-solutions around optimising the current system by expanding incumbent technology.

Building technological capabilities are critical for transition to circular manufacturing models. Reverse cycle operations (collection, disassembly, integration of products into the re-manufacturing or refurbishment, getting products out to users) are a core requirement, to create value from EoL materials and products through specialized skills and process know-how [31]. A firm's capabilities in ICT augment the overall business capabilities through establishing efficient collaboration and knowledge sharing, and improved reverse logistic set-ups. The data collected and knowledge acquired during entire life cycle i.e. information value [6], can accelerate innovation and identify more opportunities (e.g. improved product design and delivery, enhanced customers' and suppliers' know how) for additional value creation across the chain. IoT in combination with identification technology (RFID chips, QR codes) can facilitate re-integration of materials and products during reuse and re-manufacturing; simplify the core recovery process; and ease in management of different processing streams of specific products during multiple reuse cycles. CPS add to the capabilities for realizing closed-loop product life cycles and industrial symbiosis by efficient coordination and allocation of recourses (product, material, energy, water and data) in a holistic manner [32].

To operationalize the concept of reuse and Re-manufacturing, certain business level capabilities need to be considered, including product life cycle planning, Lifecycle Assessment LCA, focussed product design, embedding the mechanisms for return and collection of cores, and financial and cost modelling etc. [33]. Collectively they enable ‘reuse/re-manufacturing product thinking’ very early in the product life cycle planning [34]. The aim here is to select suitable products that can be easily and economically reused or re-manufactured, and whose after use yields high recovery value. LCA in combination with cost-benefit analysis can estimate price difference compared with producing a new product thereby revealing potential designs that may be incorporated in the early product design phase.

People are core to enacting a change towards sustainable future. They need to be flexible, competent, and creative so that companies could leverage their abilities into setting and realizing the SM agenda. Sustainability education is a prerequisite to correctly address the goals with a group of people who understand the company’s environmental performance and possess knowledge on smart use of resources and technology[30] . Educational programs at all levels may be aimed at sustainable value creation (economic advancement, improved societal benefits, environmental protection). Accessing, retaining and sharing of knowledge by individuals, as part of the education process, are other key factors to inspire and embed sustainable practices within the organisation. Further, to enhance productivity and competitive advantage, individuals need to be up-skilled and re-skilled continually.

3. Sustainable Manufacturing System Architecture

Enterprises are complex systems in complex environments, which have to be managed with complex managerial methods [35]. Enterprises and so do (sub) systems in it (e.g. MS) are constantly evolving in a context that is dynamic and difficult to comprehend [36]. An MS has to initiate plans and activities according to the signals from its context. Hence, to understand MS in a larger whole requires understanding the broader context of this system.

A firm’s external environment drives business requirements at the strategic level. Strategic business objectives (relatively long term), e.g. competitiveness, sustainability in manufacturing etc., are identified by strategic planning function at this level. Effectiveness of these objectives needs to be linked to the fulfillment of needs of the firm and its stakeholders, now and in the future. Process level requirements and performance goals (short term) are derived from these business needs and objectives. Effectiveness of goals corresponds with their relevance to and contribution towards strategic objectives. Processes thus need to be operated in a manner (technology) that achieves performance goals. Integrating sustainability in manufacturing processes means greater resource efficiency and productivity, generation and use of information and know how, and effective collaboration among processes. A variety of operations underlie these processes within PLC. These operations are performed through some supporting structure or an interlinked set of functional (sub) systems. A sustainable manufacturing system (SMS) integrates design, product development, production, marketing, logistics and reverse logistics, and other key support functions. The important point here is the compatibility of diverse functions with each other. A well engineered MS achieves multilevel goals and requirements by coordinating various functions towards desired outcomes. The essence is to contribute towards enhancing enterprise value (business sustainability, market share, environmental stewardship and social contribution) while serving the needs of all stakeholders.

Summing up all above, the architecture or formalized description of an SMS yields five elements: ‘Context’, ‘Purpose’, ‘Structure’, ‘Function’, ‘Process’. The MS has to manage interdependencies and contextual relationship among these elements on the concept of ‘system as a whole’; this concept is presented in Fig. 3.

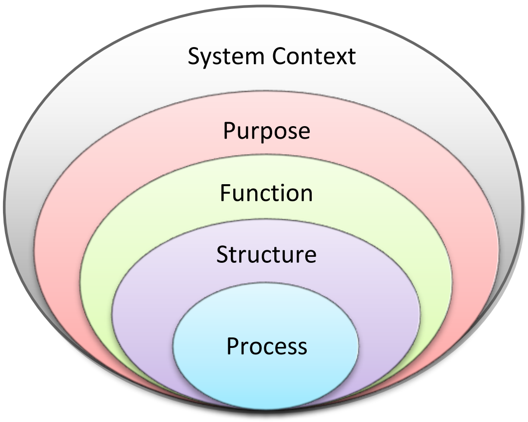

Fig. 3: Conceptual representation of system.

3.1 Context

A context is a complex whole of related parts in a socio-ecological field in which every actual happening lives [37] . It should be plausible and worthwhile, one that can be believed, and able to guide system design – MS design in this case. Context describes the unique situation of an enterprise. The main problem, however, in system design is that the context in which an enterprise exists is itself changing. An MS is contained within an enterprise, and delivers its outcomes to stakeholders. From functional perspective what MS delivers (outcomes), depends on its interaction with the context. Hence understanding the enterprise as a whole, from multiple perspectives, is important. An enterprise (collection of human and non human elements or parts, subsystems, and systems) is a part of socio-economic system which is contained within larger social system (Contained within even larger ecosystem). The enterprise relates to its context by building a logical relationship among isolated findings. These findings are then transformed into a world view or paradigm that is co-produced with the context.

An SMS needs to integrate sustainability thinking into the overall infrastructure and operations under the total lifecycle view. From this perspective an MS has to consider, in a holistic manner, all stages of life-cycle (pre-production, production, use and post-use) , all value creation factors (product, process, equipment, organization and people), technological capabilities, and organizational competence [30, 38, 39]. Within this fabric, innovative product design practices, resource conserving processes and EoL strategies have to create greater economic and social value with a lower environmental impact.

MS's boundary is a subjective construct influenced by the participating actors and MS's assumed role towards sustainability of larger containing systems (from enterprise to eco-systems and beyond) [1]. PLC boundary can be determined by the scope of activities an organization has planned throughout the entire lifecycle. However, manufacturers have the choice of including certain EoL activities in their operations or yet pay for the cost related to extended producer responsibilities, and stakeholder's perception of enterprise's value in terms of solving environmental and social sustainability problems.

3.2 Purpose

An enterprise as a system is characterized by its elements (human and non-human), and relationship of elements to one another, to the whole, and to the context. Development is the principal objective of an enterprise as a social system which serves the principal purpose of enterprise - to contribute to the development of itself and the larger containing systems [39]. In this view, purpose of MS in the larger context is to serve the purpose of enterprise, economic system, social system, and eco-system. This desire to satisfy the needs of others can be enhanced through greater competence of individuals and enhanced capability of the system as a whole. The intent or purpose of a system should be something that people find exciting and with which they are prepared to engage. Moreover, it should be defined within larger context. This systemic thinking needs a modification of the existing world view. By creating a common perception and aligning interests of elements (human), however, world view can be adjusted.

Purpose often could come from a variety of sources, and multiple perspectives. One of the main purposes of an MS is to create value for enterprise and its stakeholders by creating products and services that would create economic value, sustain the environment, and foster social fairness. From business perspective, an MS must be capable of attaining strategic business objectives, and performing existing business better. From enterprise perspective, it is expected to enhance efficiency, productivity, and competitiveness. Furthermore, it must determine what contributes to the success of enterprise, and which factors influence the behavior and performance in relation to larger containing systems. From product perspective, it should provide basis for product innovation and differentiation. At its core, however, an MS need to provide an infrastructure for sustainable production, support decisions pertaining to sustainability in manufacturing, and be more responsive to various inputs and changing context. Besides, it must look to the future of SM industry and be capable of transforming itself, to effectively and consistently meet its goals.

3.3 Function

An MS has to determine the outcome aspects in terms of what (value) is being produced and for whom (stakeholders)? Its function, at the aggregate level, is to perform a set of tasks to achieve desired outcome(s) which contribute to strategic objectives of enterprise. An enterprise has the main function of creating and distributing wealth [39].The aim is to contribute towards enterprise' growth and profitability. Effective functioning of enterprise, as a whole, could be attributed to overall set of organizational capabilities under various functional domains.

An MS turns stakeholders' needs into required functional characteristics which serve as a baseline to evaluate its technical fitness and effectiveness, in performing various functions. Sustainability requires that functions be designed to produce and deliver sustainable value outcomes to all stakeholders including environment and society. Negative impacts brought along these outcomes need to be identified and reduced throughout the entire lifecycle of products. An MS today integrates diverse functional domains across the PLC including marketing, procurement, product design and development, production planning and control, production and fabrication, logistics, reverse logistics, and manufacturing support functions e.g. QA and HRM. To attain multifaceted outcomes, as in case of SM, various functional elements engaged in producing and delivering products are required to maintain linkages. Integration of design and production and their alignment with sustainability strategy, in particular, is of paramount importance owing to its large potential to positively impact the environment and society. Furthermore, strategic alignment of functions with business strategy is essential in view of sustainability being a part of this strategy.

3.4 Structure

A firm's MS may be represented as a collection of function based sub-systems that may contain further smaller systems. Subsystems collectively form a structure for achieving strategic objectives which by now have been translated into individual and subsystem level goals. Subsystems are allocated with hierarchies, responsibilities and authorities, and provided with a combination of interdependent resources (facilities, people, knowledge assets, technology, equipment etc.). Strategic intent is effectively executed in an MS through diverse operations. Hence, understanding the relationship between structure and operating system is important [40]. The structure of facilities or plants must consider the ease in management and control of manufacturing operations.

A firm's organizational structure represents strong functional orientation, and allocation of manpower along the value-chain. Ideally, the structure should be innovative and interactive so as to produce different outcomes by the same structure or same outcome through alternate structures. Environmental and social concerns today coupled with ongoing changes in market and technologies necessitate alignment of resources and reconfiguration of structure, to produce sustainable value outcomes. But changing structure and routines, to maintain fitness to the context, is costly. Interdependent business elements (product, technology, market) could instead complement each other and respond to the changing context provided they are managed interactively. In addition, a structure must enable humans to make decisions and provide necessary and accurate information to other decision makers with the least amount of effort, cost and time. Norms and behaviors in an enterprise could enable a structure to emanate cooperation rather than competition. Effective collaboration brought about by a structure is crucial to shape: skills, diverse viewpoints, experiences and sustainability mindset, thereby creating a whole new collective understanding.

MSs are complex and often have complicated structures [35]. Complexity of this system as a whole refers to the large number of connections and influences among structural elements. There are a large number of factors on the list that add to the structural complexity [36], and affect system performance e.g. number of interfaces with stakeholders, variety of end products and number of components under each, number and diversity of product routings, and number of resources required etc. Firm's stakeholders (employees, customers, consumers, suppliers, creditors, government, regulators, other interest groups representing environment and society), their organization, number and type of subgroups within each, and influences they exercise on the system are important. Managing a large number of interfaces increases structural complexity of the system in addition to a high effort for planning. Diversity and size of customer base and extensive country-specifics and regulations are yet other factors that add to the overall complexity. Consequently, maintaining system performance becomes challenging in one or combination of these scenarios.

3.5 Process

Processes are concerned with the manner in which functions are performed to produce desired outcomes. More explicitly a process may be represented as a combination of specific sequence of steps (operations), know-how, and preferably a documented procedure to perform activities productively. A manufacturing process involves transformation of raw material to valuable goods by applying labor, energy, machines, and tools. Process outputs may be associated with parts' or- products' characteristics which can be proposed and specified likewise. From an operational perspective, a process may be described by operation description, equipment and tooling, operating instructions, and operating parameters etc.

In relation to sustainability, the aim is to develop manufacturing processes with enhanced performance (productivity, resource efficiency) and benign outputs. Processes need to be designed for maximum sustainability i.e. producing sustainable value outputs, adding value to the enterprise, environment and society, and maintaining competitiveness. Process sustainability may thus be viewed as a competitive priority, manifested in factors that affect economic, environmental and social benefits. Alignment of competitive priorities of processes with SM requirements brings such benefits as production of minimum waste, high material and energy efficiency, low processing and maintenance cost, and value adding and safe (employees, society and environment) operations. A firm needs to determine capabilities of processes against their competitive priorities so that the gaps between the two can be closed by devising an effective strategy for processes and operations. By establishing an explicit operational dependence between processes the efficiency of the organization can be maximized as a whole.

From enterprise's perspective, the aim is to establish an entire chain of sustainable operations throughout the entire PLC or as far as extend the assumed boundaries of the system. Operations quite often, however, are not designed for one set of competitive priorities or one process choice. Operations, routines and activities are interrelated concepts. Each step in the material transformation sequence is realized through an operation. Routines provide building blocks or platform for competence by repetitively performing of them using knowledge and skills. Activities underlie all the organizational routines and processes. From value chain perspective, the bottleneck and certain undesirable activities may be shed off to improve performance. Similarly, unnecessary operations may be eliminated to reduce the cost of processing. Because environment and energy have become an increasingly important consideration in design of processes, individual operations or set of operations may be modeled for optimization of parameters to produce with minimum waste and resources (energy, material, manpower).

For manufacturing businesses, the growing awareness of sustainability issues is driving the design of environmentally and socially conscious processes. In a lifecycle view, the entire process of delivering sustainable value to stakeholders may be subdivided into interrelated processes of 'design and development', 'production or fabrication', and 'EoL' processes. At end of life, one of the re-use, re-manufacturing or recycling may be a dominant choice whereas collection, recovery, sorting etc. are some of the common sub-processes under each. Products' design, their features or attributes, and how these products are made, have consequences on society and environment. Raw materials, manufacturing processes, and end of life embody most of the impact.

3.5.1 Design

A sustainable product design is aimed at designing a product that reduces costs of production, packing, distribution, product recovery, product reuse and re-manufacture while all this with an added value to business, society and environment. Although there has been a tremendous improvement in product design and development process augmented with advanced tools and techniques, yet this knowledge-intensive process is posed with challenges of reducing development time and costs in the face of competition [41]. Strategic integration of design process with other core value creation processes brings the most significant savings in manufacturing. In addition, new methods of inquiry are needed that provide deep insight into the product structure and other key areas where possible cost reduction opportunities could be evaluated. A framework, e.g. lifecycle thinking (LCT), may be adapted for an effective management of design process. This framework, in particular, enhances capabilities to determine the impact on multiple generations of a product.

Product design in relation to sustainability thinking has evolved from 'green design' to 'design for sustainability' DfX and the most recent 'circular design' (closed loop product lifecycle). DfX is concerned with designing products, based on eco-design strategies, which comply with social, economic and ecological needs [24]. Among various DfX methods, the design for re-manufacture is developing rapidly. Some of the design rules herein include economic profitability (cost of operations, retaining of sufficient EoL value); ease, time and efficient sequence of disassembly; and use of standardized components and modular designs with high recovery value [42]. There are certain key characteristics of products which can guide innovative design for reuse and re-manufacture that would ensure retaining of maximum value of used products e.g. product reliability, product durability, product modularity etc. Further, the recovery value can be increased by embedding more value in the core than the component parts so that with minimal design changes the core or base assembly can be used to re-manufacture the same product multiple times [33].

3.5.2 Production

The production stage includes set of activities and operations which convert material and energy inputs into products and services. Technology, energy, and material are the three key components in manufacturing [43]. Effective and efficient utilization of material resources and energy i.e. resource efficiency is an essential requirement at this stage [44]. Material and energy flows in manufacturing are governed by technological processes that can be improved to reduce emissions and waste. In addition, there is a need to deploy available process technologies efficiently alongside new technologies, to reduce waste and emissions through more efficient operations. Continuous improvement in resource usage, efficient utilization of materials, and processing of minimum (optimized) amount of materials may contribute to huge savings in material, energy and other resources deployed during transformation of materials. Energy-efficient production processes, and flexible and adaptable machines can increase the technological base in addition to reducing energy consumption (especially electrical). Furthermore, [2] new developments in ICT can contribute to manufacturing sustainability in various aspects e.g. production efficiency, effective evaluation and control of energy consumption, and operational safety etc.

3.5.3 End of Life (EoL) Processes

Management of EoL activities, have received a lot of attention in context of product disposal costs, extended producer responsibilities and attaining of CE objectives. EoL operations, supported by reverse logistics, after market services and remarketing businesses, enable a holistic management of the whole product supply chain towards establishing a more sustainable production system [34, 45]. After their first use, the products and materials are recovered and placed into one of the three streams i.e. reuse, re-manufacture, and recycle. Information about parts and materials (product status and content) and knowledge acquired during the lifecycle is shared to facilitate EoL processes [41].

Direct reuse is a process for continued use of a product after its first life-cycle, with same guaranty and performance as a new product, and for the same application, depending on product quality and market conditions. The objective is to deliver to the market a product that is similar to the initial one and built from the initial materials. These activities are usually carried out locally in collaboration with remarketing businesses. Direct reuse is said to have best environmental and economic advantages. The reuse production process involves collection of already-used products, cleaning, sorting, and finally testing of products to solve potential problems and ensure functionality for reuse in similar applications. The indirect use refers to using product components in similar products to reduce the usage of new raw materials [33]. Some materials and components may go to other uses (e.g. export) or cascaded into lower specification applications [46].

Re-manufacturing is an industrial process of restoring non-functioning, worn out, or traded-in products (cores) to like-new or better performance with corresponding warranty [33, 42]. Re-manufacturing (refurbishing, up-gradation) saves the value of products by recovering as much added-value from the original manufacture as possible i.e. economic value [33, 34]. The Re-manufacturing production process includes: inspection, storage, cleaning, disassembly, repair/refurbishment, reassembly, and testing/quality control [33, 42]. Based on its capabilities to reduce production costs and environmental impact, re-manufacturing is emerging among new business models in SM. Re-manufacturing may be a local activity (e.g. refurbishing of domestic appliances, mobile phones, cars etc.) or may be carried out via regional service centres. However, the quality of used products varies from product to product and may even change during the re-manufacturing process [2]. Hence, individual handling of used products, depending on their dynamic quality, can enhance the performance. To increase the re-manufacturing throughput and performance, companies may exploit additional resources by outsourcing the core acquisition process, integrating the supply chain (alignment between OEM and aftermarket divisions), and accomplishing economies of scale by sharing of re-manufacturing resources with other companies [33].

Collection systems for reuse and remanufacture must be user-friendly, and capable of maintaining the quality of materials. Leakage of materials out of the system can be addressed employing cost-efficient collection, effective segmentation, and better quality treatment systems for EoL products, thereby supporting the economics of value capture. These actions increase the utilization of physical assets, prolong their life, and shift resource use from finite to renewable sources. The difficulties in collection of cores need to be addressed by giving incentives to customers and dealers for returning the cores. Failing to collect, the products may be collected by other companies for Re-manufacturing, resulting in a loss of competitive advantage due to likely imitation of technology.

Recycling consists of recovering materials from the discarded products in order to avoid new raw material extraction and limiting of environmental impact and supply issues [33]. The recycling destroys the added-value in products and instead recovers materials only. Rather than repairing or re-using manufactured components, the products are reprocessed to recover secondary materials for return to the same use. Efficiency of recycling processes may be enhanced using environment friendly technologies [2]. Recycling may be a regional activity or part of a global supply system [46]. Reprocessing includes operations such as recycling of paper and plastics, re-refining of fluids such as lubrication oils, and depolymerisation of polymers etc. Recycling emphasizes a reduction of waste and recovery of materials that is related to environmental value [6].

4 Conclusions

SM has attracted enormous attention in recent years as a comprehensive strategy for reducing environmental impact while improving the economic and social performance. The present era requires manufacturers to design manufacturing systems that concurrently bring benefits (value) to all stakeholders including the environment and society. On this premise, a variety of aspects at the level of product, process and supply chain have been discussed in this research. Despite multifaceted research in SM, rarely are the studies that have focused on a holistic representation of an MS on the concept of ‘system as a whole’. This research has made an attempt to fill this gap by proposing a simplistic yet potentially vital concept of a system that would produce sustainable outcomes for all stakeholders. The research has overarched the SM from its core purpose and functions to value adding processes and operations. Rather merely elaborating resource conservation and environmental strategies, it has elaborated an MS down to the level of essential elements that constitute its formalized description or architecture, guided by multiple perspectives including sustainability in manufacturing, enterprise's long term sustainability, and emerging paradigms in SM.

Operationalization of the concept of manufacturing at the system's level involves necessary enterprise resources and capabilities, integrated product and process design, and management of operations and activities that underlie them. The proposed architecture has yearned for a baseline that would serve as a starting point in this regards, for an effective and systemic engineering, management, and operation of an MS in a wider context. Five structural elements of this system have been deliberated while maintaining their contextual relationship with each other, with enterprise, and with larger external context. Besides comprehensive understanding of the scope of each element, it is required to maintain traceability on how the essence of each element will drive the next, down to an effective design of processes and operations. Repetitive performing of this concept, and refining the essence or outcome of each element alongside is the key to attain long term sustainability, in actual settings. Yet there is room for further research in terms of devising a methodology to distill the essence at each of the five elemental stages. This will further add to the operational viability and effectiveness of the proposed concept.

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