

Sustainable manufacturing – An overview and a conceptual framework for continuous transformation and competitiveness

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ABSTRACT

Sustainable manufacturing is advancing amidst the changing context and emerging paradigms. Business success and longterm sustainability today depends upon transforming continuously, and maintaining competitiveness through building context specific capabilities. To address these needs, this research presented a comprehensive overview of sustainable manufacturing, in first part, contributed by numerous aspects in the field. The second part proposes a conceptual framework comprising three interconnected elements: 'Ideal', 'Strategy', 'Architecture'. The ideal is best depicted as an exploration and choice context. Synthesis of stakeholders' desires and systematic discovery of opportunities, in context of larger containing systems, manifestes into desired attributes and characteristics of products, technology and enterprise system that are to be approached continuously. The strategy element is a match and transformation context. Strategic planning, focussed on continuous identification and building of capabilities, evolves into a broader concept of the business which enhances the firm's capacity to adapt to changing contexts and meet its proposed ends. The architecture is a function and execution context at the operational level. It combines capabilities, organization and operational structure, and value creation processes to perform desired function in context of an agreed upon business concept. A systemic and potentially viable approach, embedded with specific capabilities to integrate sustainability into the core of a manufacturing business, is thus proposed which sets this research work apart. Contextual interrogation gives it a new way of constructing the big picture of the issue, i.e. sustainable manufacturing. This simplistic scheme is supplemented and guided by multi-aspect research in sustainable manufacturing, circular economy, capabilities, strategy and transformation, and systems thinking. The proposed framework is expected to fulfill the key needs of enterprises in sustainable manufacturing business, i.e. to transform and maintain competitiveness in a fast paced environment.

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1. Introduction

Manufacturing is an indispensable feature of the modern society owing to its vital strength in terms of societal service, and pivotal role in contributing towards national and global economy. However, at the same time, these human activity systems collectively consume a considerable amount of resources, and generate wastes and emissions thus affecting the environment and society [1]. It has been largely realized that natural resources and regenerative capacity of the ecosystem is not infinite. Current production and consumption patterns are being seen as largely responsible to assure a foreseeable future [2]. Consequently, manufacturing is evolving, within the framework of triple bottom line 3BL (environment, economy and society), for pursuing the big picture of sustainable development [3, 4].

ENVIRONMENT DOMAIN	ECONOMIC DOMAIN	SOCIAL DOMAIN
<ul style="list-style-type: none"> • Environmental issues (climate change, global warming, pollution, ozone layer depletion) • Eco-system concerns (waste and emissions, landfill, extinction of species, bio-diversity, restoration and conservation) • Policies, regulations and directives • Environmental performance • Impact assessment (frameworks, e.g. LCA) • Design philosophies (DfE, bio-mimicry, cradle to cradle etc.) • Resource conservation (minerals, energy, water) • Material and energy tracking (frameworks, e.g. materials flow analysis, energy flow analysis) • Strategies (waste minimization, resource efficiency, eco-efficiency) 	<ul style="list-style-type: none"> • Economic paradigm (e.g. Circular Economy) • Socioeconomic trends • Production and consumption patterns • Policies, business strategy, business model • Economic growth and development • Economic advantage, competitive advantage • Financial performance (value added, stakeholders' return, profit, potential financial benefits etc.) • Economic performance (products/operations/facilities) • Product lifecycle costs (frameworks, e.g. LCC) • Economic impact (products, manufacturing chain) 	<ul style="list-style-type: none"> • Societal needs and values, issues and trends, lifestyle and culture • Social interaction and collaboration, feedback and inputs, perspective • Policies, regulations and directives • Organization and social behavior • Social performance, responsibility, reputation • Social value, social benefits (local, national, global) • Product benefits (customer, consumer, society) • Social equity, standard of living, quality of life • Health and safety, working conditions, employment opportunities, education and training, community well-being, • Social impact (frameworks, e.g. SLCA)

Fig. 1 Sustainability aspects relevant to manufacturing business

Sustainable Manufacturing (SM from here on) involves simultaneous consideration of multiple factors and their interaction across three dimensions. Interconnectivity and co-dependence of firms with others in the entire value network even increases the breadth and overall complexity of the issue (SM), attributed to increased plurality and high degree of interdependence between elements [5-7]. Dealing with such a complex system necessitates a holistic understanding of the issue. Systems Thinking (ST from here on) is being recognized as one of the key competencies to address sustainability problems systemically across multiple domains and at different scales [8]. ST promotes holism which provides theoretical awareness of the system and avoids unintended consequences of sub-optimization [9, 10]. Sustainability, viewed as a system property, implies analysis and creation of sustainable value from the perspective of larger containing systems [11]. Yet, balancing the needs and benefits for 3BL requires robust methods incorporating an integratd analysis and evaluation of interaction among system elements. Nevertheless, exploring through vast literature, various aspects relevant to the issue (SM) are presented in three domains in Fig. 1.

Manufacturing enterprises, among others, are faced with an increasing complexity, uncertainty, change and diversity. There are a number of factors whose interplay is supposed to give emergence to this complex and diverse milieu. Naming few are; constantly shifting external environment, growing environmental and social concerns, inter-connectedness of industrial problems, faster learning and development needs, and transformation in societal needs etc. Additionally, there are concerns on rapidly depleting natural resources, and increasing price and volatility of raw materials and commodities [12]. Moreover, it has been realized that efficient manufacturing processes, technological innovation, optimization abilities, and other success factors in context of industrial production (e.g. economy of scale) are insufficient to ameliorate the overall situation [13]. Further, it has been learnt that gradual improvements at the level of product or process are inadequate to embrace long term business success and sustainability.

Sustainability frameworks and approaches, in relation to manufacturing, are generally aimed at development and implementation of sustainability strategy, sustainable business models, design and innovation capabilities, performance improvement and assessment, and decision making tools etc. Many of the proposed frameworks emphasize systemic management of sustainability concepts and requirements in context of broader systems, and a deep involvement of stakeholders. The proposed frameworks and approaches demonstrate some utility in different industrial aspects. But they lack, generally, in managing the issue (SM) holistically towards continuous

transformation and competitiveness in manufacturing enterprises. Moreover, despite widespread literature and enormous research on the issue, yet there is need to explore approaches which are potentially viable amidst the changing contexts to ensure long term sustainability. Nevertheless, researchers are learning about the capabilities of various frameworks that can bring about a change at the level of entire enterprise as a system. Numerous propositions can further increase the speed of learning and implementation.

SM businesses have to seek ways to contribute to sustainable development objectives effectively, now and in the future, while advancing amidst the changing contexts. This needs continuous support and guidance that could systematically enable the enterprise's capability to meet its desired sustainability ends. Successful transformation requires more relevant and focused designs, and a mind-set change in relation to existential purpose of the firm, its stakeholders, society and environment. A framework, however, may be established that serves as a guideline for the enterprise to create and re-create itself, to fit the proposed ends. The conceptual framework proposed in this research is an abstract concept structured by three interacting elements: 'Ideal', 'Strategy', and 'Architecture'. The 'Ideal' or ideal intent of the enterprise is chosen by stakeholders through exploration of opportunities within the contextual space. This proposition may be successfully realized provided the enterprise system is technologically and operationally capable enough and the one that can learn and adapt effectively. The 'Strategy' or strategic intent is formulated in context of ideal intent. It represents a mix of manufacturing and business level capabilities whose development and strategic deployment is potentially vital to gain competitive advantage and capture the proposed ends at large. Strategic planning and decision making is aimed towards evolving an innovative business concept that is operationally viable. The 'Architecture' at down stream converts this concept into reality. It formally describes the overall business architecture framework for SM including its functional aspects, structural issues, and value creation processes and activities. This simplistic scheme may herald long term business success and sustainability provided the concept is operationalized in a systematic and meaningful manner. The framework design and function is complemented by emerging concepts and approaches in ST, SM research and Circular Economy (CE from here on), capabilities, and various frameworks for strategy and architecture. Contextual interrogation gives it a new way of constructing the big picture of the issue, i.e SM.

Rest of the paper unfolds this scheme in quite a natural order. After the conceptual framework has been introduced in this section, the next section provides a comprehensive overview of the issue (SM) in various aspects and from multiple perspectives, to construct its contextual position. Section 3 describes proposed framework and its individual elements in detail. The relationship of proposed conceptual approach with social environment and level of economic development in a country along with its operationalization and main obstacles pertinent to a specific environment are discussed in Section 4. Finally, major findings from our discussion are drawn in Section 5, which concludes this research.

2. Sustainable manufacturing: An overview

SM has been received with even greater recognition in recent years as a comprehensive strategy for improving the economic, social and environmental performance of a firm. New management concepts (product lifecycle management and assessment, eco-effectiveness etc) , innovative technologies, and design and engineering approaches have been introduced to incorporate sustainability in manufacturing [14]. Research frameworks encompass numerous aspects at varying scale (enterprise, supply chain, manufacturing cell and operations etc.). Adopting a system design approach, Tonelli *et al.* [15] proposed a framework for sustainable industrial system involving supply chain design, sustainability performance measurement and management, and organisational change . Using DMAIC (Define, Measure, Analyze, Improve, Control) approach, Koho *et al.* [16] proposed a concept aimed at supporting Finnish manufacturing companies in realizing sustainable production while emphasizing measurement as basis of improvement. Subic *et al.* [17] developed a framework focused on development and assessment of relevant capabilities across the entire supply chain. Zhang *et al.* [7] yearned for a framework, in line with LCA and

SLCA, to integrate sustainability assessment with decision making methodology that assists in process planning at the production cell level. For sustainability in machining operations, Masood *et al.* [18] proposed a milling technique with the aim to enhance cutting tool life. Hassine *et al.* [19] presented a case study on sustainable turning operation utilizing a specifically developed multi objective optimization technique.

An emerging research interest is observed on creating value through sustainable industrial production systems (Sustainable Supply Chains SSCs and Closed Loop Supply Chains CLSCs). Govindan *et al.* [20] highlighted that reverse logistics (RL) and CLSC is now a revenue opportunity instead of a cost-minimization approach. Schenkel *et al.* [21] segregated value creation into four types of values (economic, environmental, information and customer) and presented an insight on maximizing the value by coordinating the forward and reverse supply chains. Ageron *et al.* [22] recognized that sustainability issues when integrated in SCM, as an intended strategy, contribute to business in terms of competitive advantage. Gopal Krishnan *et al.* [4] argued the necessity of devising sustainable operations along the value chain and approaching the 3BL in an integrated manner. Galal *et al.* [23] studied sustainability, mainly emission reduction, across an agri-food supply chain by developing a discrete-event simulation model.

From the system's perspective, SM needs to be analyzed in context of larger containing systems [11]. Understanding of external interactions becomes significant because of a broad range of factors across the product life cycle and their connectivity with broader systems (supply chain, market, and ecosystem) [24]. Fiksel [25] developed a triple value 3V model by dividing the physical world into three types of interacting systems (industrial, societal, and environmental), wherein the intricate dynamic linkages and flows of value among them may provide an architecture for system modelling. On the concepts of complexity theory, Moldavska [26] proposed a systemic model whereby a system contributes to not only its own sustainability, defined in terms of attractors, but also to that of larger containing system. From an operational perspective, Zhang *et al.* [7] proposed definitions and assessment framework for SM based on ST. Moldavska *et al.* [27] proposed a framework for sustainability assessment system for manufacturing organizations, guided by ST.

A sustainable product is just as effective and at least the same quality as the product it is replacing while produced using fewer resources and better materials. In addition to product's attributes, SM focuses on how the product is made, with the aim to minimize its impact. In a lifecycle view, it includes input materials, product design, production and distribution processes, and end of life (EoL) management. Within Lifecycle Thinking framework, manufacturers look beyond the supply chain to maximize the product performance throughout the life cycle. Lifecycle Engineering (LCE) is aimed at designing products that meet requirements for quality, cost, manufacturability, and consumer appeal, while at the same time minimising of environmental impacts. Product life cycle, if analysed systematically, may drive advancements in product and process technology, and other improvement strategies. Sharing and managing of product data, information and knowledge across this entire lifecycle forms the essence of Product Lifecycle Management (PLM) which seeks to integrate stakeholders, processes, resources and information in a product-centric knowledge environment, to make informed product decisions [28].

SM Principles include; using less energy and materials, using renewable energy, using fewer hazardous materials and toxic chemicals, closing the loop of resource flow, and designing products that can be easily and economically reused or re-manufactured and consume less energy during use [15]. Similar principles have been proposed by other researchers towards achieving sustainable ends. Alayon *et al.* [29] referred to 9 principles of sustainable production relevant to products, energy and material; economic performance; worker and community development; and natural environment. Esmailian *et al.* [30] referred to seven main steps proposed by Ray Anderson, to become what he called a 'Prototypical Company of the 21st Century'. For long-term sustainability, economic growth needs to be decoupled from environmental constraints through technological changes and innovation in industrial systems [31]. CE and C2C are relevant frameworks here. Based on principles of Green Engineering, they approach sustainability from an eco-effective design perspective. Principles together with relatively new economic paradigm

of CE, and manufacturing paradigms (e.g. C2C, industry 4.0), may create sustainable competitive advantage alongside a positive impact on environment and society.

Value creation in CE, as popularized by EMF, is based principally on elimination of waste and use of renewable energy during the entire lifecycle. Resource yields are optimised by maximizing the number of technical cycles (repair, reuse, or remanufacturing) and the time spent in each of the multiple use cycles of product. Increased inflow of virgin materials into the economy may be substituted by cascading or diversifying the reuse of products across value chain. Moreover, the use of uncontaminated material streams (pure inputs) can increase collection and redistribution efficiency, and maintain material quality thus improving product longevity and material productivity. Furthermore, the principle of dematerialization (minimizing comparative materials use) is at play during processes of design, making and distribution of products to ensure re-useability with lesser changes, faster returns, and higher potential savings [12]. Contrary to the linear production pattern (take, make, waste), this regenerative mode is manifested in higher resource utility and optimization while minimising supply risks and enhancing of natural capital [32]. C2C design protocol, based on the strategy of designing ecologically intelligent products and processes, offers a good premise for CE. It redefines the problem to address its source, and shifts the end of pipe liabilities to product design. A design of industrial systems on this concept necessitates flow of materials in safe, regenerative, closed-loop cycles. To achieve an optimal effectiveness close to the natural system, inputs and outputs should be safe and beneficial [33, 34]. Industry 4.0 is an evolutionary industrial paradigm centered on achieving quality, efficiency and flexibility at the same time. Businesses need to converge their capabilities, to match with this era of fast paced and broad scale disruptions [35]. The manufacturing systems in 'Industry 4.0' utilize information and communication technology (ICT from here on) infrastructure in an internet of things to deliver smart products. Cross-linked value creation modules embedded with ICT and Cyber-Physical Systems (CPS) enable efficient allocation of resources, decentralized decision-making, and efficient work design and organization [36].

SM practices are aimed at reduction in each of energy, water, waste and emissions, improved product quality, enhanced corporate image and market competitiveness, better access to new markets, reduced costs, and increased profits. Practices range from very simple process improvements to innovative product design [3], and large investments in new technologies for cleaner production. Creation of wildlife habitats, promotion of community engagement and other external practices, e.g. product stewardship can help integrate stakeholders' views into the business operations while contributing to a more sustainable world [37]. Firms primarily focus on conserving resource use and reducing physical waste which often widens to lifecycle sustainability through adoption of suitable policies and tools whereby an initial focus on internal operations grows to involve entire supply chain.

Integrating SM concepts and strategies into the core of business requires long-term decision making [29] and radically rethinking the existing business models. In a system's view, activities across all business functions need to be focussed and coordinated instead of isolated improvements in either of product design, manufacturing technology or product end-of-life management. SM strategies can be broadly categorized under the two themes or dimensions [14]; Eco-efficiency is aimed at increasing economic development through lowering of resource intensity throughout the life cycle [38] while Eco-effectivity is directly tied to the reduction of environmental or social burdens [14]. Strategies take on a different perspective at each level of enterprise. At the manufacturing process level, the focus is on improving efficiency and quality, optimization of process parameters, and reduction in processing cost. At the supply chain level, consideration may be given to the use of renewable energy across the chain, recirculation of products and materials into product lifecycles, and effective management of raw materials and services for an improvement in social and environmental impacts. At the enterprise level, the focus is on policy analysis, sustainable business development, and achievement of business objectives like productivity, competitiveness and profitability. Firms may struggle at the onset of their efforts towards SM. Yet many firms embrace an early success. Their efforts and the manner in which certain initiatives were taken could be mimicked and modelled for greater understanding.

Moreover, challenges encountered by others in the course of successful transformation may be helpful from the perspective of re-using the relevant experiences and knowledge.

Manufacturing businesses need support and guidance if they are to contribute to sustainable ends. Challenges and barriers faced need to be clarified. Future challenges include competition in terms of both inputs (resources) and outputs (products and services), diversity of customer base, rapidly changing consumer lifestyles and preferences, increasing business risks and uncertainties, adherence to regulations, avoiding use of technologies that have adverse impacts on environment, and focussing on total economic, social, and environmental cost of a product instead of low cost production [39]. The financial aspect of sustainability initiatives can be an enormous obstacle to the overall progress. Capital investment decisions need to be based on cost benefit justification because technologies required in reducing plant emissions to zero might be both complex and costly. Other commonly encountered barriers include time and resource constraints, general business concerns, and corporate culture. Aligning internal company culture with sustainability objectives in day-to-day business operations is not an easy. Manufacturing businesses need fundamental changes in their missions, and significant improvements in ways of doing business [16]. Existing strategies, procedures and standards might need a radical transformation to adapt to this new role. Transformation might need a redesign of the organization which may pose difficulties in several aspects, e.g. defining enterprise structure, boundaries, decision making processes, and resolving conflicting goals etc. [40].

Manufacturing businesses today are coped with challenges of increasing product variety and shortening product life cycles [5, 41]. While large and diversified product-mix can capture additional business opportunities, added economic benefits and enhanced consumer value, it also poses increased complexity and unpredictability to the manufacturing system. In case of SM, the concerns are even larger in terms of managing variety across the entire product life cycle. Manufacturing system's flexibility and adaptability is a critical requirement to accommodate changes brought about due to management of multiple generations of a variety of products. From the economic perspective, effective resource utilization, and integration of product design with manufacturing processes will have to be ensured to attain sustainable competitive advantage in these environments [5].

Sustainability assessment, performance measurement and reporting is a challenging task in manufacturing organizations [7, 27] due to the complexity and dynamics of manufacturing operations and diverse theoretical perspectives on sustainability requirements, often normative in nature [24]. WBCSD, GRI, OECD, ISO, UNEP etc. have developed standards and guidelines, yet there are difficulties in several aspects. GRI's general as well as sector-specific assessment and reporting guidelines need customization for their befitting to the needs of a firm and its stakeholders. Life Cycle Thinking (LCT), a more popular framework, integrates three elements – Lifecycle Assessment LCA, Lifecycle Costing LCC, and Social Lifecycle Assessment SLCA – which together provide a methodological framework for Life Cycle Sustainability Assessment (LCSA) [42, 43]. Although an LCA study has certain limitations and challenges, it is a robust and most widely used framework for evaluation of potential impacts of a product during entire life cycle [7]. However, SLCA and LCC methods are relatively less developed and lack scientific consensus – too few tools and fully developed databases are available – hence rarely conducted in process industries [43]. Despite huge amount of research in sustainability assessment, there is an absence of comprehensive, universally accepted and widely applicable metrics. Organizations find limitations in terms of interpretation and implementation capabilities relevant to a variety of tools, indicators, and metrics on the list. Organizations are even recognizing the importance of developing sustainability tools and metrics specific to their unique business environment [27]. The real value of assessment lies in attaining of sustainability objectives and providing valuable input to decision-makers rather than external reporting only [27, 44]. To avoid sub-optimization, there is a need to develop frameworks and tools, from a unified and holistic perspective, capable to assess and monitor the entire organization as a system instead of focussing on individual areas and functions. Moreover, the value added through such an endeavour should be in balance with the resources required [27].

3. Proposed conceptual framework

Continuous renewal of enterprise intent and translating it into an implementation plan is a contested problem [45]. Understanding the nature and purpose of enterprise, as a starting point, may guide in establishing requirements from a functional perspective. An enterprise as a system consists of structure and processes which collectively perform economic function, characterized by products and services delivered in context of an environment [46, 47]. The principal objective of an enterprise is the 'development' that serves to contribute to the development of itself and the larger containing systems. Greater this capacitation, better the firms can attain their objectives [48].

The framework proposed in this research is based on enterprise's desire to contribute to the sustainability of society, environment and economy, and stay competitive in relation to changing contextual position of SM. As presented in Fig. 2, the framework as a concept system contains three functional elements or subsystems interrelated with each other: 'Ideal', 'Strategy', 'Architecture', and is its self part of a larger whole, i.e the enterprise. The ideal is best depicted as an exploration and choice context. Systematic discovery of opportunities within all important business dimensions and a coevolved proposition of products and enterprise system are what underlye a holistic and clarified vision embedded with stakeholders' desires. The enhanced capacity to sense opportunities manifests into an improved understanding of what satisfies stakeholders, and which attributes (of product, system) can lead competitive advantage? The ideal intent thus evolved serves as a reference to be approached continuously throughout the transformation cycle. The strategy element is best represented as a match and transformation context. Strategic planning is aimed at identification of capabilities corresponding with opportunities; formulation of policies and guidelines to enable an effective and efficient use of enterprise's means; setting of business objectives and goals; and commitment of resources and assets. The desirable consequence of this planning process is a broader concept of the business. Continuous identification and development of capabilities enhances capacity to adapt to changing contexts. The effectiveness is reflected in the speed and degree to which specific capabilities can be created and matched with opportunities. The architecture, at the operational level, is a function and execution context. It combines capabilities, organization structure and business processes to perform desired functions in context of an agreed upon business concept.

The context of the issue (SM) and hence the ideal intent keep changing. In response, the strategic planning reformulates the business concept and renews relevant capabilities. The architecture reconfigures capabilities and assets to adapt to changing business needs. This continuous process harnesses the capabilities and collective learning of the enterprise as a whole under dynamic business requirements. By operationalizing the individual elements and managing interaction among them, a manufacturing enterprise can be transformed continuously and systematically in relation to its desired sustainability ends. In subsequent part individual elements are explained in terms of their relationship with each other and with larger systems. Various aspects of SM are discussed alongside as deemed relevant to the nature and scope of each element.



Fig. 2 Structural representation of framework

3.1 Ideal

Sustainable products should not only be safe for environment but also create opportunities for life-systems, in addition to satisfying the needs of business and society. Determining what the environment (life system) actually wants, to attain its own ends, is beyond scientific deliberation, and seems unattainable. Nevertheless, businesses can approach this limit by consistently turning social needs and desires to environmental advantage specifically, rather merely creating opportunities that could positively impact [49]. This could serve as an ideal to be approached endlessly. Apple has recently pronounced to move its entire supply chain to closed loop and renewable energy in the wake of undeniable climate change and depleting earth resources. Though it seems unattainable currently as the report says, "It sounds crazy, but we're working on it", Apple has embarked on its journey by launching projects related to capabilities enhancement and technology development [50].

An SM enterprise delivers in context of a hierarchy of larger systems: industry (economic system); marketplace and society (social system); and eco-system or environment. Stakeholders' interests can significantly drive manufacturing towards sustainability and competitiveness [51]. This whole system's view helps understand the way a manufacturing enterprise interacts with its surroundings, throughout the entire life cycle of products. More pragmatically, however, the ideal can be chosen in relation to opportunities within present and future context of SM, continuously changing business environment, and SM principles, practices and industry challenges. Because external environment keeps changing, it necessitates proposing of products and technology in a larger context, i.e. emerging social and environmental needs, and trends and changes in business environment (e.g industry drivers, technological innovation, product lines and competitive priorities etc.). This concept is presented in Fig. 3. Through this systemic inquiry, stakeholders' desires can be translated into full range of potential business opportunities, and desired properties and boundaries of enterprise system. To validate the content of a proposed ideal, interactive planning (IP) suggests two means: 1) inter-subjectivity and consensus among stakeholders with regard to a proposal, and 2) experimental feasibility [52].

Creating a vision is a key requirement for successful organizational change, consistent with Ackoff's notion of an idealized design. Re-design and transformation are desired consequences of a thoughtfully synthesized vision. External vision (insights, beliefs, and assumptions) is based on interpretation of all the factors in the context that have an impact on firm's operations and performance. Context can be viewed as a field of related parts [53], constructed for an issue, say SM. Descriptions of contextual pattern within this socio-ecological field form the present context. In regards to future, scenarios are chosen that describe alternative, comparably plausible lines of changing overall field conditions. Although there is no way of designating the one future that is most likely to emerge [54], scenarios can facilitate cognition of multiple possible futures in concrete detail and guide the context specific design of new business concepts or innovating around existing ones. Business environment is a sort of design space, a context in which to conceive or adapt the business. In fast-paced competitive environments, assumptions about how market forces, industry forces and emerging trends unfold give us the design space to develop potential business options [55].

The broadened scope of activities in SM, and large number of actors along the value chain necessitate all concerned to have a voice in decisions pertaining to products, technology, market, and enterprise system at large. Guided by System's methods relevant to stakeholders' engagement, and Ackoff's interactive planning (IP) and his view of the organization as social systemic in nature, the process of co-creating the ideal intent can be made more valuable. Firm's stakeholders and their participation are centric to this process. We need to understand stakeholders' needs and interests, and progressively combine them. By establishing a generative context for the engagement of diverse perspectives of multiple stakeholders, a synergistic proposition can be evolved that is meaningful in a context of use [56]. An important insight is that no participative process can include every possible perspective, i.e. comprehension is impossible. In an interconnected world, knowing about any situation has limits or boundaries [57]. In relation to system boundary, we need to determine what is in our control, who (people and issues) is to include, how to justify exclusions, and how to address marginalization.

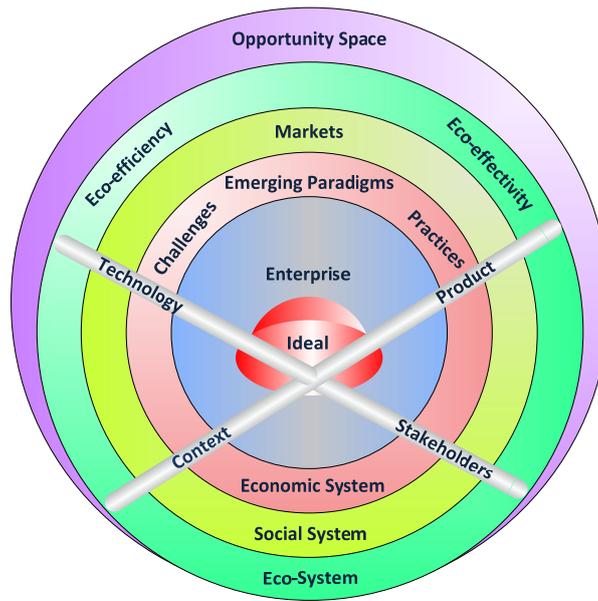


Fig. 3 Evolving system ideal

3.2 Strategy

An enterprise’s quest towards its ultimate ends is corresponding with the capabilities possessed by its ends-seeking system. Strategic intent of the firm is sought mainly to convey the purpose of the enterprise and how it is expected to perform in relation to those ends. Strategic objectives set the direction for designing business solutions and shaping operational structure [58]. Policies govern the selection of means and instruments by which the objectives are to be pursued, and principles are formulations of values to be preserved in such selections [48]. Principles provide guidance in making strategically consistent choices from the perspective of sustainability. Capabilities, derived from strategic principles, are a core concept to communicate and realize strategic intent. Building of capabilities has emerged as a new approach under strategic planning [59] to maintain competitive advantage and attain long-term business sustainability in a turbulent environment. A firm needs specific capabilities to enhance its capacity to create sustainable value and adapt to changing circumstances faster than competitors. The strategic planning process, using ideal intent as as a set of inputs, yields strategic intent manifested in an agreed upon business concept. This process is presented in Fig. 4. Capabilities identified in this process are built alongside to enable meaningful execution of this business concept. Capabilities are superior business processes, represented as a set of knowledge, skills, and competences [60]. The capability of organization as a whole is a high-level routine (or collection of routines) which combines tasks from different business functions into a particular output or solution of significant importance to the firm [61]. Capabilities not only provide a platform for strategy but also impact growth and profitability which in turn provide means for further strengthening of them. For the manufacturing sector this view of strategy has important bearings on organization’s skill base, and dynamic decision making especially on infrastructural aspects [59]. The principles, policies,



Fig. 4 Evolving strategic intent

and systems of actions, underlying the infrastructural choices (Organization, manufacturing planning and control, quality, new product introduction and human resources), govern and reinforce the capabilities and resources that affect a firm's operations.

Strategic importance of building capabilities is being realized beyond mere competitive reasons due to a shift in strategy focus from decreasing costs to increasing added value [62]. To embrace sustainability as a new business opportunity in manufacturing, a firm's key management function is to bridge the gap between strategic intent and required capabilities. Capabilities need to be developed in all of the important business dimensions (product, market, technology etc.) to capture entire range of opportunities. The future of manufacturing industry is characterized by capabilities in skills development, CE, technology and innovation, supply chain integration and digitization. Pre-production (R&D, product design) capabilities include those to develop innovative product concepts and its supporting technology. Within production segment, overall capabilities can be added to by undertaking fabrication of increasingly complex and innovative products, flexible operations and optimized process planning, and improving resource efficiency through new fabrication methods. In post-production segment, capabilities are required in terms of efficiency and reliability to perform marketing, distribution, and EoL activities [35]. Both the individuals' learning capacity (competence) and capabilities of the organization are central to innovating the business in more sustainable ways and accommodate new needs of sustainability. Table 1 illustrates these capabilities along with salient requirements to attain them.

Table 1 Capabilities for sustainable manufacturing

Capability	Salient requirements
Integrating sustainability into the core of business	<ul style="list-style-type: none"> • Adopt a business perspective, and transform the traditional business mindset. • Innovation in business to turn environmental and social concerns to competitive advantage without incurring increased costs. • Articulate and maintain a holistic view of sustainable value aimed at proposing a balanced value and distribution of economic costs and benefits among all actors. • Judicious commitment of financial resources to investment opportunities. • Create differentiated and innovative business models and enhance capacity to create, adjust and replace business models.
Identification and evaluation of opportunities	<ul style="list-style-type: none"> • Gathering and filtering of information from both inside and out side the enterprise, and from core as well as the periphery of relevant business environment. • Comprehending the likely evolution of industry, technology, and marketplace. • Establish search and discovery methods and procedures, and allocate resources. • Enhance interpretive skills of individuals and learning capacity of the organization. • Assessment of relevant opportunities through decision rules and informed conjectures.
Building of individual skills and competence	<ul style="list-style-type: none"> • Education and training focussed mainly on internalization of sustainability concepts, creative and innovation abilities, functional capabilities and life-cycle-thinking. • Building of cross-domain skills (technology, engineering, electronics, robotics, computational and computer sciences) to perform manufacturing functions in industries of future. • Cost-effective, innovative and exploratory teaching methods, e.g. in-person training and coaching, experiential environments and digital methods. • Adopting a structured approach for capability alignment and assessment, i.e. tools, methods, procedures, quantitative targets, credible metrics etc.
Operationalization of CE	<ul style="list-style-type: none"> • Culture adaptation, transition processes, and strategic direction to appreciate difficulties. • Technological capabilities for an improved reverse logistic set-up aimed at high value recovery. • Strategic use of ICT to establish an efficient collaboration and knowledge sharing. • Capitalizing on information value to accelerate innovation in design, and identify more opportunities for additional value creation across the chain. • Product life cycle planning with a clear focus on product reuse/re-manufacturing. • Understanding materials (formulation, quality, innovation etc.), and a broader integration of material science into the business case and across value chain.
Product design & development	<ul style="list-style-type: none"> • Effective management of design process within a lifecycle thinking framework. • Capture and reuse the knowledge acquired throughout the lifecycle to modify existing designs. • Understanding the criticality of decisions at early stages of design in view of lifecycle costs. • Use fewer materials, renewable materials, non-hazardous materials, and substitute materials. • Evaluate materials against chosen criteria, e.g. service life, recoverability, separateability etc. • Design products that consume lesser resources during production, packing, distribution, recovery, reuse, re-manufacture and recycling. • Evaluate competing product designs for price and ecological impact. • Design products that are re-usable, re-manufacturable, recyclable, and bio-degradable.

Table 1 (Continuation)

	<ul style="list-style-type: none"> • Evaluate reusability, and remanufacturability of design alternatives via pre-determined criteria, e.g. technological and economic feasibility, and environmental benefits. • LCA, cost-benefit analysis and financial modelling to reveal potential designs for incorporation. • Incorporate design for sustainability (DfX) and other strategies, e.g. design for upgrade, design for disassembly, design for modularity, and design for reliability etc.
Production and delivery	<ul style="list-style-type: none"> • Innovation and flexibility in production and process technology. • Choose and develop production processes that are efficient, resource conserving, processing of minimum material, and less polluting. • Understand technology, energy and material as three interrelated components, vital to improving resource efficiency. • Effective deployment and use of innovative technologies (e.g. ICT) for process control, energy saving, production efficiency, and safety etc. • Efficient transportation and logistics to reduce environmental impact and cost of distribution.
End of life (EoL) management	<ul style="list-style-type: none"> • Establishment of reverse logistics activities, and their alignment with after market and remarketing businesses. • User friendly and cost efficient collection and segregation depending on product quality, and effective segmentation to support dynamic recovery and economics of value capture. • Capitalize on knowledge acquired during lifecycle to facilitate EoL processes. • Devise processes that enable product re-usability with minimum possible resources to gain best environmental and economic advantages. • Leverage external resources to increase the throughput and performance of EoL processes, e.g. outsourcing the core acquisition, integrating the supply chain with aftermarket divisions, and accomplishing economies of scale in re-manufacturing by sharing resources with others.
Standards	<ul style="list-style-type: none"> • Establish norms and rules that lead to a significant reduction of activities and transaction costs. • Strategic use of standards to add to the firm's capabilities and manufacturing base, re-engineering of the technology and processes, and redesign of products. • Adoption of international standards towards a faster knowledge acquisition and technological transition. • Establishing uniform standards along the value chain for standardization of product-related information, complete life cycle assessment of products, sustainability performance evaluation of all upstream and downstream partners, and optimization of end product sustainability. • Efficient collaboration and data exchange, distribution of right information in a fast and reliable way, and holistic management of complex tasks through the use of communication standards.
Alignment and collaboration	<ul style="list-style-type: none"> • Extending capabilities in terms of exploiting additional resources through broad-based external search and close interaction and collaboration with other enterprises, entities and institutions in the business environment and society. • Strategic involvement of customers in product design and development with the aim to include their perspective in value proposition, discover new opportunities and business models, develop more successful and radical value creation solutions, reduce product costs, anticipate the potential for applying new technologies, and retain customers longer. • Extending capabilities in terms of exploiting additional resources or shifting certain activities (e.g. procurement, product design etc.). • Establishing strategic partnering with supplier to capture benefits of economies of scale by outsourcing to contract manufacturers and large suppliers, assimilating the capability of suppliers in terms of those capabilities that are closely linked and mutually reinforcing, capitalizing on rapid innovations by component suppliers ahead of the competition, improving supplier operations, and optimizing supplier-manufacturer interface to reduce material costs and gain a better insight on environmental impact reduction opportunities along the supply chain. • Leveraging benefits of co-specialization and complementary innovations towards differentiated product offerings and unique cost savings, improved performance, sustainable competitive advantage, and enhanced entrepreneurial capacities.

3.3 Architecture

The architecture serves the purpose of realizing an agreed upon business concept, formulated as part of firm's strategic intent. It links business strategy with business roles and processes, and structures the responsibility over business activities along the value chain [46]. It determines effectiveness in attaining firm's objectives keeping in view their strategic impact. From a functional perspective, it manages interaction among structure, processes and activities, and resources and capabilities to deliver sustainable value to all stakeholders. This concept is presented in Fig. 5. Within its functional framework, it utilizes a common and preferably customized knowledge base that allows manipulation of information about different business aspects from a variety of perspectives.

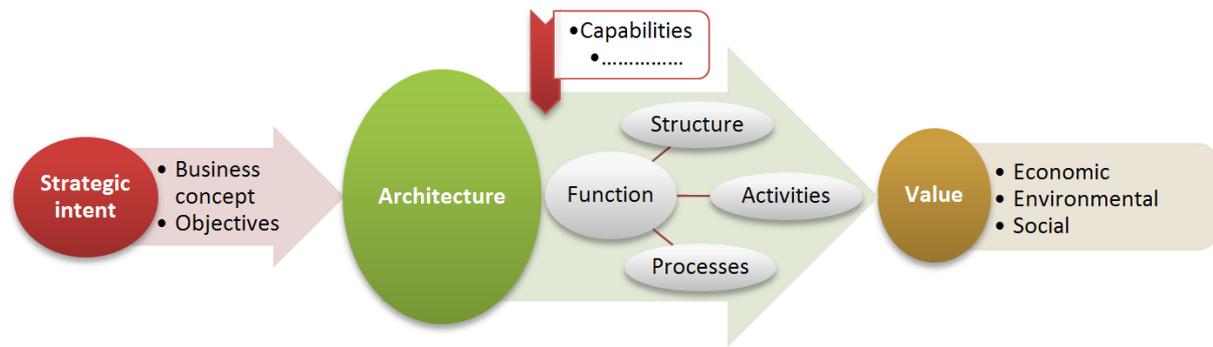


Fig. 5 Architecture framework for sustainable value creation

In system's view, architecture design involves a holistic understanding of how function, possible structures and processes should interact and communicate with each other to produce desired outputs, within a larger context. The planning, learning, and control function is thus an integral element here, responsible to evaluate the effectiveness of organization as a whole [10]. In functional design process, a comprehensive review of the strategic intent is conducted first to understand business priorities, relationship among objectives and transformation requirements. BA role is then determined in relation to business needs including required capabilities and core activities. The detailed business analysis next establishes a clear view of the business in terms of its organization and value chain structure. The final solution dictates initiatives (e.g. investment analysis, new product rollout, capability outsourcing etc.) and measurement criteria relevant to set objectives. This process, however, is ongoing and continues to redeem the once finalized structure, processes, activities and even the business concept. Analogous to Checkland's [63] abstract concept of 'system as an adaptive whole', an architecture responds to the changing needs and requirements, interactively manages the value creation factors, and establishes a fit between problem space and proposed solution. The desirable emergent properties characterizing such a system could be, e.g. a unique and differentiated business value or improved sustainability performance etc.

Environmental and social concerns today, changing market needs, technological innovations, and capabilities based competition are driving manufacturing businesses towards sustainability. Structural flexibility on the other hand must complement the prevalent dimension of the competition; based on either of new product offerings, market dominance or technological leadership, towards an efficient and conflict free internal environment. A multidimensional mode of structure – capable of producing different outcomes in the same or different environments – can interactively manage the interdependent business dimensions thus eliminating the need for a change of emphasis from one business orientation to another [10, 48]. [45] Strategic intent is interdependent with firm's operational structure which establishes relations between people, process, technology, managerial aspects, and information. The operational structure must ensure that wealth creation, cost reduction, and environmental and social performance are improved simultaneously to support the sustainability strategy.

Processes are primarily concerned with how the actual output(s) is to be produced through an integrated chain of activities performed by different groups in an organization, with a strong interface among them. Processes are technologically driven and subject to continuous change and improvement. A firm must comprehend the relevance of technologies to emerging competitive challenges, understand the flow and interface between system elements, and acquire operational knowledge of processes. In addition, these technological processes should maintain compatibility with already in place organizational processes that are concerned with creating integration, alignment and synergy among the parts of an organization [10]. A firm's core competence (unique resources and strengths) drives its core processes. In case of SM, the core processes in the chain include design and development of new products, production and delivery of products, and EOL management. Salient requirements in terms of capability of these processes have been illustrated in Table 1. Each process must be designed to achieve its priorities. Operational effectiveness of these processes may be assessed with key metrics corresponding to those

key activities in the value chain that influence the critical dimensions of sustainability performance. In addition to key activities, the firm needs to perform other essential activities, e.g. to train its workforce, to develop new capabilities, and to link new activities to the existing activity system [64]. The nature of products and services, and the activities performed to deliver them collectively determine the structure of value chain [46]. The choices on content, structure and governance of activities shape the architecture in terms of where these are to be performed and what kind of resources are required to perform them? The entire collection of activities can be managed conveniently by aggregating them at different levels (major functions at top-level and specific activities at lowest level) [64], or segregating them according to their core, supporting or peripheral nature.

4. Discussion

The proposed conceptual approach rests on some key tenets, elaborated in section 3, which collectively could enable long-term sustainability (ability to transform and maintain competitiveness) for manufacturing businesses; among them greater capacitation of businesses to contribute to sustainable development, understanding stakeholders' needs and interests, a coevolved vision and business proposition, enhanced capacity to discover opportunities systematically, learning capacity, competence and adaptability of individuals and organization, building of context specific capabilities in all core segments of the business and their strategic use towards creating added value, innovative solutions and faster response to changing market needs and technological challenges, and holistic understanding of problems and solutions in a larger context to improve economic, environmental and social performance simultaneously. The existing social environment and level of economic development of a country could be relevant/ significant in view of implementation of proposed concept across its entire manufacturing sector. Specific strategies and policies that consider both economic growth and social development are vital to nurture an environment for sustainable business development. Leading a competitive advantage demands educated and competent manpower. Quality of education has a direct impact on skill levels of individuals. Equal opportunities for education, training, employment and health increase productivity and growth. Exploration and capturing of new business opportunities is a knowledge intensive and entrepreneurial endeavour. National policies for matching skills with business needs could add to the ability of businesses to transform and create new value. Strong financial means in a country and better access to those, along with other supporting conditions, may encourage entrepreneurship and pursuits of competitiveness and innovativeness. National spending on research and development could pave the way for strong collaborative networks in a society which foster co-creation.

The proposed conceptual framework serves as a guideline in enabling continuous transformation and competitiveness of a manufacturing enterprise. However, it is not an implementation methodology or a procedure in itself that explicitly defines any preference as to how to get there. It will be instantiated using a chosen or developed methodology; conceptual frameworks, generally, do not include or imply any process model for implementation. Nevertheless, useful insights have been drawn from relevant research in reference to enterprise. First, formalization or standardization of proposed framework's elements, in context of specific manufacturing environment, is critical for its consistency and common understanding across management levels and common people. An explicit management procedure may be established to enable systematic implementation and execution through relevant tools and techniques. Potential challenges and any unforeseen conditions or obstacles, posed by the dynamics of the external or internal environment, may be identified. Building a robust culture of sustainability is vital to successful implementation of proposed concept. Sustainability education and skills in the domain of change management and organizational behaviour are critical to deployment process. Top level management must lead the implementation process to elevate its status. Employees who understand day-to-day business routines may be encouraged to get them involved in generating innovative ideas. Implementation objectives should be defined. Moreover, it needs to be assured that specified initiatives and activities contribute to transformation goals throughout the course of im-

plementation. Communicating to the employees and other stakeholders that why the company has chosen this continuous transformation path, i.e. “ideal—strategy—architecture” is essential. Pertinent here is to frame and relate stakeholders' apprehensions in an understandable form. Company wide communiqué, at the bare minimum, may include business needs, implementation issues and requirements, and expected benefits of such a transformative change or redesign.

Despite above recommendations, an average manufacturing environment may yet face multiple challenges on the way to become a sustainable competitive firm in accordance with transformation path proposed in this research. Capturing opportunities for sustainable value creation and building and evaluation of capabilities (Table 1) are no less than a paradigm shift for such environments. The proposed concept is centred on sustainability being a core component of the business (strategy) along with its continual renewal to gain long-term success while average manufacturers most often target short-term economic gains. Nevertheless, a deliberate support from government and society, in various aspects, could play a significant part to bring them at par with proposed requirements through a systematic incremental approach. Identification and evaluation of opportunities (idealization stage) could be a knowledge intensive and costly affair posing resource constraints. This process may be facilitated through a network of manufacturers, researchers and domain experts thereby helping traditional manufacturers seek alternate products and new markets to create competitive advantage. Experts in cultural assessment and change management can assist in developing and promoting a company culture needed for integrating sustainability into the everyday business. Government can sponsor participation mechanisms during idealization and strategic planning stage that could enable businesses to create new value innovatively with existing resources instead of huge investments in new technology. Evaluation of resource efficiency and lifecycle impacts needs specialized skills wherein provisions can be made for free of cost availability of such services. All such initiatives, at significantly low cost to businesses, could motivate them towards implementation of proposed concept.

5. Conclusion

Despite enormous research on SM, rarely the studies have focussed on continuous business transformation according to stakeholders' desires while maintaining competitiveness in a changing context. This research tried to fill this gap by first recognizing the need for a holistic and systemic representation of the issue along with a potentially viable approach embedded with capability to integrate sustainability concepts in manufacturing. A comprehensive overview of the issue, contributed by numerous aspects, provided an overall design context. A holistic and integrated process of planning and realization was aspired in relation to sustainability goals and a systematic transformation. Ultimately, framework was designed to provide a simplistic and progressive approach that could produce consistently the sustainable outcomes, and meet proposed ends. The three elements that jointly constitute this approach, i.e. 'Ideal', 'Strategy', and 'Architecture', have been presented from their functional perspective and contextual relation with each other and larger context. A systemic platform is thus established by constructing and operationalizing the individual elements. The dependency and relationship of elements with each other drives the conclusion that when executed in isolation, each element could still create value but limited to its context of use and initiating choices. The holistic view can maximize the cumulative sustainable value by managing the interaction among its elements, and maintaining the traceability from proposed ideal to strategic intent, and finally to architecture which has implications for functional effectiveness of the enterprise. Transformation can be more effectively achieved and repeated by accomplishing what is necessary and in concert with stakeholders' desires within each of the three elements. The enhanced capacity of enterprise to satisfy these requirements is the key to attain proposed sustainability ends. Continuous identification and re-novel of capabilities build this capacity to exploit opportunities for sustainable value creation.

Embracing this conceptual framework and its systematic operationalization will drive continuous transformation of a SM business in a fast paced environment. It also seems fair to conclude that proposed framework can play a critical role in maintaining competitiveness since it

suggests several capabilities whereby challenges can be addressed through meeting salient requirements underlying each capability. However, the framework is not yet embedded with methodology, procedures or tools for implementation, and there is room for further comprehension in terms of implementation strategy. Further research is needed in actual settings to confirm whether it can achieve the claimed objectives in diverse manufacturing environments. The experience so gained will demonstrate its conceptualized role of integrating sustainability requirements and addressing challenges, pertinent to manufacturing businesses.

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