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The role of system of systems in additive manufacturing

By

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The role of system of systems in additive manufacturing

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The rapid growth in additive manufacturing technologies have brought various optimization techniques and methodologies to improve each phase that needs to be integrated and analyzed on system level to optimize the system performance. The challenges and limitations of each phase affect the system when integrated as a whole - creating a complex manufacturing environment that needs to be critically examined and managed. To have a better management of complex, emergent, and uncertain manufacturing system from design to recycling phase, a new way of thinking based on more holistic approach is necessary. In this paper, the system of systems paradigm (SoS) is introduced to treat additive manufacturing system as a whole and to present some SoS approaches that are based on holistic thinking. This paper provides a conceptual knowledge of SoS approach using systems principles, laws and approach emphasizing the characteristics and attributes of complex manufacturing system to the AM domain.

Key words: complex system, system characteristics, challenges, limitations, design phase, manufacturing phase, supply chain phase, recycling, remanufacturing, system principles, case study, conceptual framework

DEDICATION

I would like to dedicate this thesis to my parents for their love and support in every aspect of my life. A special word of thanks goes to my friends, family and fellow members whose continuous support and encouragement made it possible for me to complete this work.

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CHAPTER I

INTRODUCTION

The requirements of customer customized products with shorter lead times and faster response have challenged traditional manufacturing methods such as forming, casting, molding, machining etc. to adopt various technologies to meet customer expectations. The competitive and challenging economic environment has affected almost every industry sector to adapt flexible product development, reduce material and equipment cost, adapt to changing customer demands, reduce lead times, reduce inventory costs and improve logistics, thus leading to the appeal for an advanced flexible manufacturing method [1]. A possible solution to these challenges and future innovation is delivered by a new technology known as Additive manufacturing (AM). Additive manufacturing is a process of fabricating a part from a three-dimensional (3D) models in a layer-by-layer addition approach [2]. Additive manufacturing is being used in various industrial applications such as aerospace, motor vehicles, machinery, electronics and medical products [3], [4]. This technology has been growing rapidly in the industrial sector because of its various advantages and capabilities over traditional manufacturing methods such as efficient material use, waste minimization, design freedom with less constraints, low energy consumption, and reduced time to market [1], [5]–[7]. AM provides better alternative to the traditional manufacturing methods like machining, injection molding, die-casting, because of its ability of directly building part from a digital representation enabling rapid fabrication of highly customized parts without the use of additional fixtures and cutting tools [5], [8]. Design and fabrication of complex parts and assemblies is now feasible with this technology.

With the growth of AM technology, many researches [3], [9]–[13] have been conducted to investigate the performance improvement of AM system on different phases that constitute the product lifecycle from design, manufacturing, logistics, to recycling. However, these studies are currently limited to sub-system level optimization which cannot provide enough infrastructure to optimize the overall performance of the AM system in the complex environment, thus requiring a system level perspective and analysis on this new technology [9], [13]–[22]. Huang et al. [20] have called for implementation of AM technologies with integration of interdisciplinary knowledge to understand the interactions between materials and processes. Frazier [21] acknowledged the positive impact of AM on the environment and specifies the needs for systems approach which spans the cradle to grave lifecycle of AM products in order to understand true benefits of the new technology. Each sub-system has its own advantages and limitations that may affect each other when integrated as a whole system. To balance these phases' advantages and limitations, product life cycle cost should be analyzed from a system level instead of individual sub-system level [1]. This continuing trend of optimizing each sub-system suggest the need for a new paradigm of thinking commensurate with the new realities. This new paradigm is necessary, and represents an opportunity to critically examine and offer a new way of treating and managing manufacturing system (from design to recycle).

To have a better management of manufacturing systems as a complex, emergent, and uncertain, from design phase to recycling, new way of thinking that is based on more holistic approach is needed. In this paper, the system of systems paradigm (SoS) will be introduced to treat AM system as a single unit, present some SoS approaches that are based in holistic thinking, addressing the design, analysis and transformation of multiple manufacturing systems from a SoS holistic approach. To explain this SoS paradigm in light of AM system, this paper will

1. Introduce the system of systems perspectives (SoS) as it related to manufacturing. We believe that introducing SoS to manufacturing provides a new opportunity for better design, analysis, and management of product life cycle as a complex system of systems. While several existing studies focus on the use of additive manufacturing from a sub-system optimization level, this papers present a new SoS paradigm that focuses more on holistic approach and treats manufacturing as a complex SoS.

2. Present the main characteristics of complex systems from a SoS point of view. We emphasize that these characteristics are already exist in manufacturing systems, and therefore failures in AM system can be attributed to a combination of these characteristics.

3. Show how the holistic systems based approach, which considers the spectrum of design, manufacturing, logistics, and recycling, can be used to treat the manufacturing system life cycle as a whole unit. This stands in contrast to treatment as separate and independent (for analysis) sub-systems in manufacturing.

4. Enhance better design, integration, and analysis of AM systems through a holistic system of systems engineering approach

This conceptual research paper presents the System of Systems (SoS) approach to the AM domain to attain three main objectives: (I) contribute to the body of literature by stimulating more holistic decisions making based on treating AM systems as a whole unit using the SoS principles, laws, and approaches, (II) and link the SoS paradigm to manufacturing systems and treat AM system as a complex system of system. This would provide new mindset, toolset, and methodologies to AM system from SoS perspective. Two case studies are presented to analyze the complex system attributes and SoS principles towards aerospace and biomedical applications. Prior to present the role of SoS paradigm in AM systems, the next section will demonstrate the concept of SoS and its main characteristics.

To achieve these objectives, this paper is organized into five chapters to present the role system of systems engineering methodology in additive manufacturing. Following the introduction, chapter 2 presents introduction to system of systems and its definition, chapter 3 provides the overview of SoS development and current state of art studies on each phase of AM system. Chapter 4 presents the AM system complexity by exploring the SoS characteristics. Chapter 5 describes the manufacturing system of systems with the help of two case studies. Chapter 6 presents the SoS principles and laws that provide foundation for the AM system.

CHAPTER II

SYSTEM OF SYSTEMS

The interaction between two or more systems in order to achieve performance, purpose or behavior that requires support and coordination leads to system complexity. This type of system complexity cannot be fully understood with physical and mathematical laws. To understand the complex nature and to function accordingly, all systems should be treated as a whole using a holistic approach in conjunction with General System Theory laws and principles [23]. A shift beyond traditional reductionism based thinking is necessary to be focused on the whole rather than isolated elements to address complex system problems [24].

A system of systems (SoS) is an approach that presents a high-level viewpoint and explains the interaction between each of the independent systems. It is a super system that consists of various sub systems or elements which themselves are independent complex operational systems that interacts among themselves to achieve a common goal [25]–[27]. This SoS technology effectively implements and analyses large, complex, independent and heterogeneous systems working cooperatively. Here, each element of an SOS achieves well substantiated goals even if they are detached from the rest of SoS.

Over the course of it evolution history, many definitions and perspectives were proposed for the term system of systems (SoS) [24]. The systems concept was first used by Smuts (1926) using the term "holon" to describe the whole and parts of a system [24].

Berry et al. defined SoS as a general system theory for all system where the concept of wholeness, control etc. started that were beyond the capability of mathematical models [28]. This concept provided a new way to understand general principles for all systems that developed with a level of uncertainty. Different theories emerged following the notions of term “holon” and idea of general system theory. The need to deal with the increasing system complexity and to move beyond traditional reductionism based thinking brought the notion of SoS. System based methodologies emerged that focus on treating the system on a holistic approach. The first use of term “system of systems” was used by Strategic Defensive Initiative in 1989 to describe an engineered technology system [26].

Eisner et al. [29] utilized the new term SoS in their work in “computer aided system of systems engineering” to define SoS as a set of several independently acquired systems that are interdependent and form a combined operation of multifunctional solution to a common mission of overall system optimization where individual system optimization doesn’t guarantee overall system of systems optimization.

The definition of SoS is also governed by the perspective in which the technology is utilized such as biological perspective where there is struggle for autonomy of individual systems in a large entity, social perspective where individual systems voluntarily integrate to constitute a SoS, and also military point of view, where integration increases individual system effectiveness [24].

The general thread running through these perspectives and definitions is that heterogeneous, integration, large-scale, evolutionary, network are the terms used to describe SoS. These traits are also present in additive manufacturing system. AM is a complex system, with heterogeneous elements such as design, manufacturing, transportation, recycle or remanufacturing that interact and communicate with each other to improve the overall system performance. The emergence of unexpected behavior of an element during system interaction leads to complexity and uncertainty.

In absence of systemic view, each element faces challenges in analyzing functions and decision making. In AM design requires information from other systems in order to utilize AM benefit and provide sustainable design of the product. But without the governance of the information and system process, none can fully benefit. In a system level perspective where each system engages towards overall system performance, each individual system benefit from each other. Each system appreciates the intricacies of complex problems and be able to function in systemic perspective. This systemic worldview leads to better thinking, decision making, actions in a complex environment [24], thus, emphasizing the need of SoS in complex AM system.

CHAPTER III

MANUFACTURING SYSTEM PHASES: SYSTEM OF SYSTEMS OVERVIEW

Manufacturing system consists of various phases through which a product passes during its lifecycle. These phases have their own importance, advantages and challenges. These phases must be analyzed individually to understand the need of SoS. In AM system, the SoS consists of different phases such as design, manufacturing, supply chain and recycling or remanufacturing. Majority of research have been done in design and manufacturing level Limited or few researches have been done in supply chain and recycling aspects. But these studies have been limited to individual phase optimization and lacks integration and incorporation of other phases. To understand the SoS need and current state of art studies, in this section, we identify current developments in the different phases of AM system along with current challenges and limitations to facilitate the significance of system of systems approach to the research problems. Figure 3.1 shows some opportunities and challenges of additive manufacturing.

OPPORTUNITIES

- Unprecedented design flexibility, allowing customization and new product development
- Consumerization/personalization of manufacturing
- Novel end-market applications in areas such as regenerative medicine
- Relocalization of US manufacturing
- Rapid product development and deployment
- Improving process sustainability (fewer yet greener materials; less energy and waste associated with production)

CHALLENGES

- Exuberance vs. natural evolution and true potential of the technology
- Ethical considerations (e.g., guns, bioprinting of human cells)
- Intellectual property/privacy issues
- Regulatory uncertainty in different countries
- Limited choice of materials
- Materials and process manufacturing qualification and certification standards
- Small production runs and scalability limitations

Figure 3.1 Additive manufacturing opportunities and challenges

Additive manufacturing opportunities and challenges [30]

3.1 Design phase

Design is the initial phase of the product life where the product concept is modeled into design files that contains product information such as geometry, characteristics, lifespan and more. Design phase consists of designing, computational cost for optimization, prototype validation and labor. The material choice and properties requirement is also determined at this stage to obtain optimum design and quality product. The products' physical and geometric information are included in a CAD file that is propagated to later stages. Several design optimization methodologies have been proposed [13], [14], [31]–[35] together with concept of Design for Additive Manufacturing (DFAM) to optimize the design to enhance product performance and minimize cost. One of the goals, is to understand each processes' challenges and limitations and utilize that information while designing, thus improving the product fabrication process. This would decrease complications and facilitate later stages and even for remanufacturing [36]. Researches have been concentrated in improving the design phase of AM since it is the key phase that determines the requirements and results on the later phases. It is critical to understand the product flow along with the challenges and limitations of later phases at this stage, as it not only affects the later stages of manufacturing (i.e. recycling), but also determines the performance and characteristics of these phases. AM have provided more freedom to the designers to design various parts with complex shapes and various geometrical features [31], [37]–[39]. New concept of DFAM approach facilitates new designers with new possibilities, advantages, and challenges to explore new design spaces [20]. Number of researches have been done in creating design methodologies to utilize these advantages in the manufacturing environment [13], [14], [16], [31], [34]. In AM, design has a great impact on part quality, manufacturing time and cost. The relation between parts surfaces quality and manufacturing sequence have been studied to understand the relation to manufacturability. Structured methodology can help designers consider all manufacturing constraints and suggest appropriate design for AM [40], [41]. Ability to produce any geometrical shape without the need of milling and turning planes and cylinders, manufacturing of complex part, ability to consolidate part, reduce weight, customize functionalities, personalize with aesthetics without compromising mechanical properties, on demand manufacturing and inventory reduction are some of the manufacturing capabilities [14], [31], [37], [40], [42]. Likewise, manufacturing cost and time, usage and removal of support structures, energy consumption, propagation of digital files and information, material selection, accessibility and heat dissipation, post processing requirements are some of the manufacturing constraints [13]–[15], [31]. Understanding these capabilities and constraints, Vayre et al. [31] have proposed four step methodology: analyzing specification, initial rough surfaces creation, shape optimization and design validation for designing process. Likewise, Doubrovski et al. [37] have proposed Three Link Chain Model (3LCM) that provides reasoning framework for design highlighting the distinction between processing, structure and properties, thus relating the product shape and structure with performance. Oettmeier and Hofmann [40] have proposed a new DFAM methodology that considers functional specifications and process characteristics which allows designers to choose manufacturing direction and manufacturing trajectories as key elements for global approach to determine the geometry that optimizes the use of chosen AM process that is chosen. With this method a CAD model can be generated that is designed for the AM process not limiting to initial design. Various authors have stated the importance of topological optimization in design stage that solves material distribution and part specifications and can be used to achieve optimum shape design that can maintain final weight and structural properties throughout the lifecycle of the product [14], [15], [43]. Although, AM has enabled high degree of freedom for designs, current technology limits potential due to various constraints, insufficient tools and less information from the later stages. The CAD systems should be reinvented to overcome the limitations of parametric, boundary representations, and solid modeling in representing very complex geometries and multiple materials [20]. The accessibility and heat constraints limits the design space such as having curves instead of sharp edges, avoidance of closed hollow spaces, necessity of powder removal from part [31]. Minimizing support structures is difficult for complex geometry and also require different optimization approaches such as topological or parametric optimization which is expensive and requires automated optimization in time intensive parts [13]–[15], [41], [44]. One of the main constraint at current development stage of AM is flow of information within the AM systems. Currently, STL file format is used as standard for data transfer and communication but it’s disadvantages such as lack of process information, ability to hold basic geometry information only, problem in conversion from CAD files and loss of information while conversion has opened up a new challenge for communication and information transfer to and from each phases of the AM system [45].

3.2 Manufacturing phase

Manufacturing or fabrication is the next phase where parts are made in layered approach. Layered fabrication process started with rapid prototyping and evolved into direct manufacturing of metal parts because of the ability to produce customized, sustainable products in low volume and less inventory. It enables the ability to fabricate replacement parts quickly when needed in cases of urgency such as army needs, hospital needs [46]. Here, the digital representation of the product obtained from design phase through CAD file is fabricated layer by layer using various AM techniques such as Fused Deposition Modeling (FDM), Binder Jetting (BJ), Selective Laser Sintering (SLS), Stereo Lithography Apparatus (SLA), Laminated Object Manufacturing (LOM) and Laser Engineered Net Shaping (LENS) [12]. Optimal process parameters are defined to build the product effectively utilizing less energy at minimum cost. The manufacturing operation structure (i.e. centralized or decentralized) is determined by the size, demand, consumer location and preferences, and supply methods, and also depends upon the features of design and logistics phase. This phase consists of material, planning, equipment usage, energy, labor, inventory and post processing. The fabrication related cost plays a major role in analyzing the performance of the overall system in this phase. Although, the technology is not yet mature, the part quality differences are substantial from one machine to another depending upon the type and cost of machine in terms of achievable mechanical and dimensional properties and their characterization [18]. Studies are mainly done in understanding the manufacturing cost, energy consumption, environmental aspects, production constraints, production flexibility, build time, labor requirement and post processing requirements to analyze overall cost and performance of AM system. The freedom in design have provided the ability to produce fewer number of parts with fewer assembly steps without much production tools impacting production costs and performances [47]. Ability to manufacture complex parts directly from a digital representation without tooling, machining, molding, die casting and with minimum waste awards AM to be more environment friendly [48]. To evaluate the environmental impacts and sustainability of AM processes, studies show different methodologies on assessing energy consumption of tools during fabrication and environmental flows such as material, fluids, electricity [49]. Mani et al [8] have examined the potential impact of AM and proposed an outline for sustainability characterization guide that provides measurement framework for improvement. The characterization guide involves understanding process physics, collecting relevant data, performing sustainability analysis and comparing with other processes to set action plans for improvements. Le Bourhis et al. [48] modeled and evaluated the environmental impact using an example of wall manufacturing. The study method considered part-process approach to account for initial environmental impact and proposed a minimization of the impacts by modifying part's design and process parameters. This method provides designers, ability to optimize part's design to reduce environmental impacts. To integrate these type of models into design loop, Le Bourhis et al. [9] developed a concept of Design for Sustainable Additive Manufacturing (DFSAM) to evaluate electric, fluids and raw material consumption of a part directly from a CAD model. Apart from environmental impacts, energy related researches shows promising results and huge potential of AM. Machine type, material type, data preparation, pre and post processing requirements are the main performance drivers in AM. Using business process analysis and time driven activity based costing model [10], [47] developed a life cycle costing model to understand and rate the cost drivers on six major stages (concept, design, production, installation, usage and disposal) of the product life among which operation and maintenance phase were the two largest contributors. Build time depends upon the machine type and availability, utilization and the size and shape of the part along with cost of material used and energy consumed. In a systematic Life Cycle Inventory data collection approach, [46] Kellen et al. found two dominating features – building height and volume as dominant design features that influence energy consumption. Mongnol et al. [49] showed that the part's orientation into the build volume plays an important role and could increase the electric consumption of the machine reducing the system performance. Peng et al. [12] studied the energy consumption of 3D printing process in the context of environmental impact using analytical approach to estimate total energy consumption and to optimize energy efficiency with minimal environmental impact without compromising quality requirements. However, limited data study on energy consumption has hindered the progress in accurately evaluating the energy consumption of various processes [12], [48].

3.3 Supply Chain or Logistics phase

The product then enters the logistics phase where distribution methods are analyzed and optimized depending upon the demand characteristics and product design [50]. The unique manufacturing characteristic of AM has created a new perspective in supply chain system. The product distribution may be sent directly to the customer or distributing centers. Different supply chain configuration strategies can be applied to improve the system performance [11]. This phase includes logistics cost, transportation and holding facilities cost that are dictated by other phase's characteristics. The supply chain network design depends upon the product design, production line design and facility design [50]. Depending upon part design and customer need, centralized or decentralized production patterns impact the supply chain network. AM can provide lean supply chain system through just in time (JIT) manufacturing and waste elimination [5]. This technology can reduce the inventory requirement over long period of time especially for the service parts as it can be fabricated anytime when needed. It can also be used to reverse engineer replacement parts to restore old equipment such as aircrafts with better or same design [43]. Currently, limited researches have been done in biomedical and aerospace sector to evaluate the performance of this phase in AM system. Fabricating parts at or near the customer location reduces inventories, lead time and logistics and provide flexibility on unpredictable customer demand without additional cost [11], [43][10], [39]. [11], [51] have studied the cost breakdown in distributed AM supply chain system and proposed three configuration strategies such as hub manufacturing, production postponement and internet based customization and distribution, to mitigate the implementation problems and reduce operational cost, and improve system performance in the spare parts supply chain. Khajavi et al. [51] studied the impact of evolution of AM technology on spare parts supply chain of air cooling ducts using four scenarios of current and future, centralized and decentralized supply chain configuration on total operating cost. The study showed potential advantages for distributed production system subjected to lower machine acquisition cost in future.

3.4 Recycling or remanufacturing phase

Recycling or remanufacturing is the final phase that the product undergoes depending upon the product characteristics which may be recycling or remanufacturing subject to design and cost. Remanufacturing is an important aspect of manufacturing. It can save up to 90% of materials and also retain high portion of value of the parts originally manufactured [36]. Not only that, it also has a potential of sustainable production and economic improvement in developing countries. The cost and profit of remanufacturing depends upon the design and manufacture of the product as 70% of the product life cycle cost is determined by the end of product design stage [36]. Reduced lead time and less cost capability makes remanufacturing attractive to improve overall system performance and cost. AM hugely benefits in remanufacturing because of its ability to add materials not only to repair but also to improve part quality and functionality. Large and expensive products usually undergo repair process [19], [52]. Some repair may involve redesigning of some parts, whereas, some may require remanufacturing. Matsumoto et al. [36] have discussed some trends and challenges of remanufacturing in AM perspective and specifies the necessity of designing the product for remanufacturing. Various other literatures have also emphasized on Design for Remanufacturing (DfRem) guidelines, methods and tools that determines the re manufacturability and cost associated with it in a life cycle thinking approach [52]–[56]. Wits et al. [55] presented a new approach on sustainable end user maintenance of AM parts by optimizing maintenance, repair and overhaul strategies. The authors presented one standard process flow and four end user optimized process flow that allows end users to shorten circular economy loop and optimize equipment parts and usage according to their specific needs. The paper shows a case study of repairing pneumatic cylinder and addresses the advantage of AM technology in fabricating need specific space parts to optimize the process rather than replacing with standard OEM parts.

The table below shows the summary of the key challenges and limitations of each phase and their impact on the overall AM system.

Table 3.2 Summary of key challenges and limitations and their impacts on additive manufacturing system

Phases	Challenges and Limitations	Impact on AM System
Design	Design parts to reduce manufacturing cost, time and material usage	Design freedom advantage can be utilized to improve build time, material usage during fabrication phase. Based on design, building height, volume and special features the energy consumption varies.
	Design parts to reduce weight and material usage without compromising part quality.	Single assembly design reduces assembling cost by reducing number of parts to build and assemble without affecting functionality
		Single assembly design decreases transportation cost by reducing number of parts to be transported
	Design parts to reduce support material usage	Reduces material cost during manufacturing phase that improves efficiency. Self-supporting design reduces post processing requirement and material usage.
	Overcome accessibility and heat constraint	Reduces cost during manufacturing stage by facilitating post processing process
	Material selection	Depending upon material selection manufacturing time and characteristics change

Table 3.2 (Continued)

		Affects the repair feasibility and re manufacturability.
	Propagation of digital file and information to and from other phases	Lack of physical and digital information exchange between all phases of AM system causes difficulties in optimization and system performance. Forward and backward information flow facilitates in better design and alleviates fabrication issues. The physical information in the digital file improves supply chain management in both product transportation and repair. Feedback to design with process capability and logistics management would benefit on better design of products.
	Utilize different optimization techniques to improve shape and size during design but the capability of current CAD software and system not able to utilize AM advantages.	Optimal shape and size helps on logistics management as well as fabrication. Better CAD system should be re invented to optimize part geometry. Part cost is proportional to the volume of the part that can be optimized.
Manufacturing	Main challenge is to minimize build time, material usage, electricity usage. Part orientation in build volume also affects build rate and part properties	It also affects the supply chain management on lead times and
	Part quality differences are substantial due to different type and cost of the AM machine	Part quality may not be able to meet design requirements.
	Limited data available on energy consumption and environmental impacts	Less information for other phases to achieve optimal specifications. These data play important role in redesigning or repairing products.
Supply chain	Production pattern affects supply chain management. Distributed production supply chain is a better option but only benefits with future evolution of technology. Current higher machine cost, less automation, and less design optimization calls for centralized production system	Production configuration determines the manufacturing, logistics as well as repair phase. Distributed configuration has fabrication process at or near customer location that reduces inventories, lead times and flexibility on unpredictable customer demands
	Current AM machine acquisition cost is high and personnel intensive. Distributed production is expensive	Not all part design can adopt distributed configuration. Manufacturing locations have to be determined considering equipment cost and customer locations. Machine capacity becomes critical to improve performance.
Repair or remanufacturing	Part repair, recycling or remanufacturing ability depends upon part design and fabrication ability	Repair / re manufacturability must be considered during design as repair is one of the major advantage of AM system. AM ability to add material can not only repair but also improve quality.
	Proper guidelines, methods and tools for re manufacturability and cost based on life cycle thinking approach is needed	Improve system performance and reduce overall cost with Design for remanufacturing guidelines. It can provide feedback to design on part quality and functionality improvements.

Summary of key challenges and limitations and their impact on additive manufacturing system

All these phases optimization activities need to be interrelated and integrated to form a single manufacturing system. The requirement and performance of one phase affects the other leading to a complex system. The decision made during design of a product affects later phases. Depending upon demand, customer location, and initial cost, production pattern may be centralized or distributed [51]. The part shape and required equipment size may dictate the production pattern due to cost and productivity. Small parts manufacturing can be done with small equipment where as large size parts may require large and advanced equipment. Distributed production pattern may be utilized for small parts to improve supply chain management and reduce lead times whereas for large size parts, large equipment is needed that may not be feasible due to increase in cost. Similarly, centralized production for high volume may reduce the system performance due to high capacity requirement and costly logistics. Likewise, distributed pattern may benefit towards small parts design, increase productivity, less lead time and inventory but only few percentage of small part may be repairable depending on its mechanical and usage requirements. This shows that the form of production system and supply chain structure needs to be determined on a system level. Manufacturing large single-part and supplying to customers with certain repair percentage may be expensive than manufacturing small parts and assembling. In some cases, where volume is low but lead time and cost is high, fabricating large parts in few locations would be beneficial. Production method may increase or decrease supply chain cost. The design of part may or may not be feasible for distributed system. In order to analyze these characteristics (production system, supply chain system, repair system), one cannot determine the optimal solution by looking at single system. Optimizing a single phase may not optimize the overall system due to the complexity of the system. Acknowledging the necessity of systems perspective, Kim et al. used a systems approach to identify system level requirements for the development of integrated information system architecture that will provide a platform to enable the verification and validation for AM information across digital spectrum [56]. The paper studies the industrial needs in terms of system integration and proposed a conceptual information architecture to address the interoperability between the digital formats during the product life cycle [56].

In summary, the interrelation and interaction between the mentioned phases create a complex manufacturing system where complex system attributes hinder the overall performance of the system. Complex systems including the complex manufacturing system have a combination of both technical (technology) and non-technical aspects (culture, social, politics, power etc.). The non-technical dimensions would affect the overall system performance. Several optimization methods and techniques can be utilized to optimize each phase of the sub-system (i.e. design phase) however, when integrated the sub-systems as a whole unit, the existing optimization methods may not achieve the same level of success. The systems' dependency on the overall system performance has to be analyzed from a system level. This paper is not meant to criticize the current optimization techniques, but rather to focus attention on the necessity to shift beyond tradition reductionism-based approaches (i.e. optimization approaches) to develop more rigorous solutions to advance our capabilities in dealing with complex manufacturing systems from a more holistic way. Thus a more holistic approach has to be taken to determine the best possible solution. An integrated manufacturing approach is needed to analyze the overall system and solve the 'wicked problems' that are the byproduct of modern complex manufacturing systems. After discussing the role of each phase in manufacturing systems, the next section will show the SoS characteristics in AM systems.

CHAPTER IV

SOS CHARACTERSTICS IN AM SYSTEM

The objective of this section is to present additive manufacturing as a complex system of systems by exploring the SoS characteristics. The system complexity may be present in different ways. To analyze the system in a "systemic" level, the characteristics that lead to complexity must be analyzed. These characteristics are defined as complex system characteristics that arises in any complex systems. These characteristics are pieces of information that like quality or features regarded as a characteristic or inherent part of something. Jaradat et al. [23], [57] analyzed and coded more than a thousand resources, using a scientific inductive approach, to derive the main characteristics of SoS. The results of the coding analysis done by Jaradat et al. in 2014 & 2015 produced seven main characteristics that constitute a SoS based on the history and evaluation of SoS from 1926-2012 [23], [24]. As shown in figure 4.1, these characteristics are *interconnectivity, integration, evolutionary development, emergence, complexity, uncertainty, and ambiguity*.

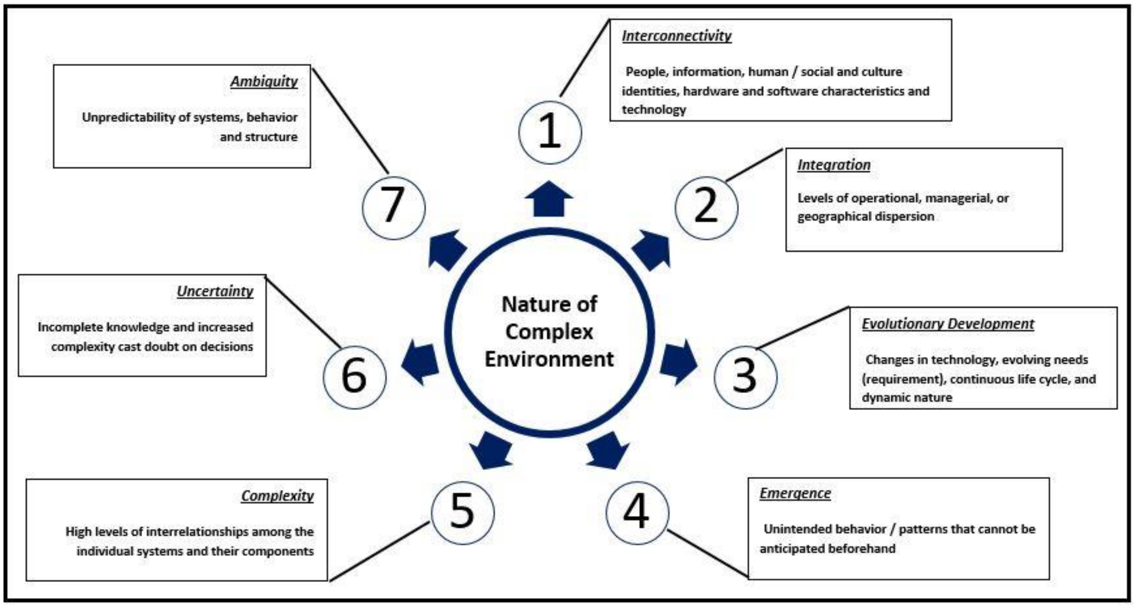

Figure 4.1 Seven main characteristics / attributes of complex manufacturing system

Seven main characteristics or attributes that constitute a SoS on a complex manufacturing system

4.1 Interconnectivity

Interconnectivity means the interaction between different systems that could have similar or conflicting perspectives. These interactions could be social, political, technological, cultural, informational or human that includes divergent world views. In AM, different systems interact and interconnect with each other. Design influences on the mechanical, geometrical and aesthetic features of the product while manufacturing phase tries to optimize the fabrication and environmental costs. Each phases’ perspective inter connects with each other to establish as a single system. As information increases, human interaction increases, the system becomes complex with complex interconnectivity.

4.2 Integration

Integration is the process through which a component or subsystem becomes a part of a larger entity and accommodates its traits to a greater whole. This integration can be of any element, component or systems. In AM, the whole system is a combination of different sub systems such as design, manufacturing, logistics and recycling. Each phase becomes the part of a whole system and needs to perform as system rather than individual entities. In complex manufacturing system, the integration process connects all phases to optimize the overall performance of the system. The properties of the whole system may be beyond those held by individual entities. To optimize the overall cost in AM, design alone cannot fulfill the requirements. Although, each phase is optimized to reduce cost and improve efficiency, their integration may not achieve similar result as different challenges and limitations emerge because of the system complexity.

4.3 Evolutionary development

The effect of various direct and indirect factors impacts the complexity of the system. This may lead to resources imbalance to the system and may require balancing or reallocation. This process can be defined as evolutionary development where the shifts in the system can be mitigated with evolution of needs and necessary re allocation. In a complex system like AM, the uncertainty in customer requirements, location may lead to rapid shifts. The part design may be optimal but due to manufacturing or transportation issues, necessary changes may require to optimize other processes. In some cases, the limitation of different sub systems may require further development necessities to improve the whole system.

4.4 Emergence

As the complex system operates, interaction, uncertainty and complexity becomes apparent. Unplanned and unwanted behaviors and patters evolve that hinders the performance of the system. These behaviors weren't discovered beforehand and is visible as a complex system operates. In AM, these unintended patterns can affect any stage of the system. At logistic phase, any delay in delivery may result in loss of customers and loss in business, while sudden increase in customer may lead to production capacity and transportation issues.

4.5 Complexity

The technological and non-technological aspect of AM system and their interrelationship with different phases leads to complexity of the system. Different factors on each phase, their patterns, constraints become complex when integrated as a whole. The constant need of feed forward and feedback of information within the AM system creates complexity in the system. External influences such as customer demands, customization, conflicting objectives of systems influence and constrain the development of a solution.

4.6 Uncertainty

In a complex system, incomplete or lack of information leads to uncertainty of the system. The outcomes or constraints that weren't anticipated hinders the system performance. In AM system, the current technological development is not enough to understand the rare events and emergence in a system. The nature of equipment to use during fabrication makes difficult for design to accommodate the equipment limitation onto the product design.

4.7 Ambiguity

The lack of clarity between different phases of the system casts doubt in decision, action and interpretations in a complex system. The lack of information flow within the system leads to ambiguity while assessing as a whole system. In AM, manufacturing phase requires not only geometric information from the design phase but also the physical, process and tessellated data. Lack of information transition from one phase to another lead to uncertainty thus increases complexity in the system.

CHAPTER V

DESCRIBING A MANUFACTURING SYSTEM OF SYSTEMS: TWO CASE STUDIES

Table 5.1 Case studies summary table

No.	Case Topic	Design	Manufacturing	Supply Chain	Recycle/ Remanufacturing
1	Air cooling ducts			x	
2	Prosthesis development	x	x		

Table showing case studies and their implications on manufacturing phases

5.1 Case Study I: Aerospace application

Additive manufacturing is a great opportunity for the aerospace industry because of its manufacturing advantages of complex light weight structures and traditional design challenging parts. The main challenge is to reduce weight while maintaining the structural integrity and functionality. One way to overcome this challenge is to fabricate a structure having a shell of a defined thickness with a lattice structure in its interior that would reduce the weight. And to achieve this conventional method is difficult but additive technology facilitates direct fabrication of lattice structure with gradual and controlled porosity [6]. In aerospace, the traditional process is expensive and highly wasteful which can be improved by means of AM. AM decreases the cost of fabrication significantly with great advantages such as reduction in use of raw material, reduction in buy to fly ratio, freedom from geometrical constraints, reduction in use of energy and more [6]. In a comparative study done by Reeves et al. among traditional and selective laser melting process, the product fabricated from latter process had the same mechanical properties and 40% less material [58]. The following case studies looks at the challenges and understands the information on each phases of the AM system along with the system attributes that emerges.

5.1.1 Case study of air cooling ducts (spare parts supply chain)

One of the first implementation of AM in final product manufacturing is air cooling ducts produced as functional spare parts for F-18 Super Hornet fighter jets. This case study is a part of research done by Khajavi et al. [51] to evaluate the potential impact of AM on the configuration of spare parts supply chain system.

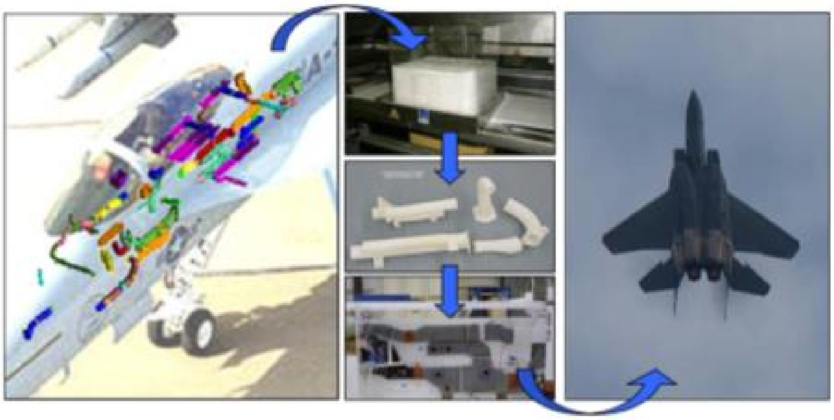

Figure 5.1 Aerospace application of AM parts in F-18 aircraft

Design, production, testing and implementation of additive manufactured parts (air – cooling ducts), deployed in F-18E/F aircraft [51]

The study is accomplished through scenario modeling of real life spare parts supply chain in aerospace industry comparing the total operation cost including downtime as the performance measure. In order to reduce production cost and shorten the planes' manufacturing cycle time, selective laser sintering (SLS) additive manufacturing technology was used. Utilizing one of the capabilities of AM, different ducts were combined into single part creating complex geometries and fewer parts without compromising the functionalities that aid in shorter lead time, shorter installation and weight reduction.

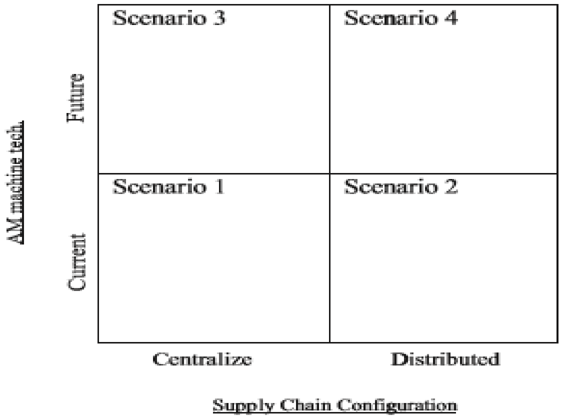

Figure 5.2 Supply chain configuration

Four scenarios supply chain configuration on overall cost and performance analysis [51]

In this case, as shown in fig. 5.2 below total of four scenarios in two dimensions: supply chain configuration and AM machine technology, were modeled and the total operating costs (including downtime costs) were compared. The cost components in each scenario consists of personnel, material, transportation, inventory, downtime, inventory obsolescence and inventory production [51]. The total cost of current and future AM machine was analyzed between centralized and distributed supply chain configuration where future AM machine is assumed to have lower acquisition cost and smaller production chambers. Overall, shifting the spare parts production pattern towards distributed system benefits by reducing overall operation costs, lower downtime, higher flexibility, reduced inventory and more energy efficient [51].

Utilizing seven main characteristics of SoS approach, the air cooling ducts spare parts supply chain system in overall AM SoS is explained.

5.1.1.1 Interconnectivity

The supply chain of air cooling ducts is connected with the production pattern and location of production facilities and Naval air stations. The result showed that at current situation with high machine cost, labor intensive and large production chambers centralized spare part production is more efficient than distributed. Whereas, in future situation when machines are cheaper and more automated, the distributed supply chain system provides more significance [51]. This interconnectivity and conflicting perspective upon interaction of customer demand and manufacturing ability attributes towards AM SoS. AM infrastructure that has design information, centralized or distributed production facilities, equipment specifications production rates, automation level, customer facility logistics information enables the AM SoS to perform better in all phases reducing the total operating cost.

5.1.1.2 Integration

The spare parts supply to the naval air station and master jet base can be either from a single production facility or be manufactured in all locations. The transportation and inventory cost is low for the later process. On the other hand, with central production facility the equipment cost is lower than having machines in all stations [51]. These two contradicting scenarios require integration such that they share the same goal of improving system performance while individually optimizing their own success criteria. SoS encourages to access the impact of machine development in the reduction of overall cost while determining the supply chain configuration.

5.1.1.3 Evolutionary development

In spare parts supply, the production configuration, personnel cost, material cost, aircraft downtimes have direct or indirect impact on the system that leads to complexity. The demand uncertainty may impact the material cost, downtime cost and also in inventory. To mitigate this issue, reallocation of resources is necessary that affect other phases in system. Part design may have to change or production capacity may need to change to accommodate the uncertainty. Individual phase optimality shifts towards system optimality to improve the whole system. In air cooling ducts supply chain, increase in automation and improvement in AM machine specification is important to maintain overall system performance [40], [51].

5.1.1.4 Emergence

In a complex system, uncertainty leads to unwanted system behaviors that hinder the performance. In supply chain, any logistics delay, delivery loss, loss of customers, sudden increase in demand, machine failure affects the system. Machine downtime can lead to delivery delay, personnel turnovers and increase in material cost can increase the operation cost. In the AM SoS, these emergent behaviors can be addressed within the phases to overcome the losses. Change in production pattern in manufacturing, changing design to reduce build time, increasing automation can mollify the emergent effect on overall system performance. Also, changing the specification of AM machines potentially enables distributed production that provides customers with faster after sales services lowering the total cost [51].

5.1.1.5 Complexity

The interaction between different phases, their technological and non-technological aspects influence each other and may constrain the development of a solution in the system. Each phase has their own challenges and limitations that may conflict with each other causing system complexity. External influences such as customer demand, customization may increase conflict within the system. In the case of air cooling ducts, small increase in salary of AM machine operators can bring higher total cost for distributed production configuration [51]. With the help of AM SoS, the salary threshold can be determined that ensures overall system performance with efficient supply chain configurations.

5.1.1.6 Uncertainty

Lack of information from each phase may result unintended behavior and patterns that affect the system performance. In AM, current technological development is not enough to understand the rare events and emergence in a system. Traditional mathematical models have limitations that may not be applicable in AM system, that increases uncertainty level causing delay in decision making. In F-18 Super Hornet environment control system, the AM machine acquisition price and personnel intensiveness are major obstacles in the deployment of the technology [51]. This uncertainty affects the manufacturing phase in raw materials and pre- and post-processing labor costs.

5.1.1.7 Ambiguity

Lack of clarity on the essential aspects of the system casts doubt in decision, action in a complex system. Lack of information flow within phases of the system creates ambiguity on individual phase decision making process for optimizing the system performance. In case of supply chain, unknown production configuration, inadequate part design information, customer demand and location etc. rise ambiguity that hinders not only supply chain but also the overall system performance. In the case of air cooling ducts, lack of AM machine specifications, and less information on pre- and post-processing affects operational cost and efficiency [51]. AM SoS tools can provide proper guidelines to clarify and improve communication between all phases that eliminates ambiguity and improves performance.

5.2 Case Study II: Biomedical application

AM ability to fabricate highly customized parts with short fabrication series is ideal for biomedical sectors. Since, implants are highly personalized and unique to the human body, AM can provide those requirements. Not only customized complex and personal parts fabrication, overall product development is also faster than traditional process with less human error [6]. Surgical intervention time is also reduced, where all the necessary adjustments of the implants can be made using the model before the surgery avoiding risk of more than one surgeries. Gradual structures can be fabricated easily employing lattice structure. Porosity and density of the part can be maintained through AM process [59]. This technology is growing its popularity in implant fabrication market such as dental structures, body osseous structures. Use of titanium has been prominent for biomedical application as it fulfills strength and stiffness, corrosion behavior and process accuracy requirements [60]. Current challenge in this field is testing and certification which will be more visible as technology grows. The following case studies looks at the challenges and understands the information on each phases of the AM system along with the system attributes that emerges.

5.2.1 Case study of femoral prosthesis development (design and manufacturing)

The use of AM in biomedical application has been positive on joint replacement of hip and knee. Hip joint is the major weight bearing joint and manufacturers have offered various designs of prosthesis at variety of standard sizes. At least 10 percent of the populations require prosthesis of different sizes and requirements in which due to manufacturing constraints sometimes surgeons have to settle for less optimal fit [17]. A case study done by Maji et al. [17] shows the development of patient specific femoral prosthesis using AM in comparison with traditional CNC machining.

Figure 5.3 Rapid Prototyping (SLA) model of hip prosthesis

Rapid prototyping on the fabrication of hip prosthesis [17]

Figure 5.4 Fit check of rapid prototyping part for hip prosthesis

Fit checking of hip prosthesis part fabricated using rapid prototyping into femur bone

In the study, a customized femoral prosthesis was developed through computed tomography (CT)-3D CAD-RP-rapid tooling (RT)- investment casting (IC) route using stereolithographic technique to understand the advantages of AM on application and benefits on the overall design to implantation lifecycle.

Hip replacement patients require custom hip prosthesis that provides better fit and longer in vivo life. The cost of customized prosthesis through traditional manufacturing method is high because of which manufacturers offer different design in certain standard sizes. This affects the functionality and longevity of the prosthesis. Any complications due to mismatch could lead to aseptic loosening, improper load distribution and discomfort [17]. Also, research shows that custom prosthesis in young patients provide higher success rate [17]. For optimal performance, the femur prosthesis should be proper fit that matches the dimension of femoral stem through femur canal. Thus, the requirement of highly individualized custom fit, dimensional accuracy, product strength and porosity, surface roughness etc., creates complex environment for manufacturing. Here, the design affects the overall process of fabrication and transportation. To understand this complexity, seven main characteristics of SoS approach are utilized to explain prosthesis development as a systems challenge.

5.2.1.1 Interconnectivity

The development of femur prosthesis starts from the CT scan of the femur bone. The structure and physical properties of each prosthesis depends upon patients age and bone structure. The load distribution and dimensional requirement for snug fit on the canal cavity has to be analyzed. Patients with good quality of bone may require shorter length prosthesis while weaker bone structure may require different structure in order to minimize stresses to proximal bones [17]. This affects the cost of manufacturing as well as quality of the product. Understanding this interconnected relation between patient bone structure, prosthesis design and build process provide better design and manufacturing benefit that not only benefit patient but also overall AM system. It helps AM system to achieve quality parts with optimal cost and better system performance.

5.2.1.2 Integration

AM has now enabled fabrication of metallic prosthesis directly from CAD file. In order to achieve an optimal design, CT scan of femur is required along with FEA analysis. The design of femur bone is not universal as the function and requirement varies with patient bone quality and structure. The optimal design achieved through CAD may not suffice patient’s requirement. The design obtained utilizing FEA for best results may not be feasible for fabrication or the build time and build rate may get affected. To minimize these effects from each individual process, and to achieve a common goal of quality, strong part all the stages must be integrated and optimized on system level.

5.2.1.3 Evolutionary development

The application of AM in biomedical sector has provided a great benefit on prosthesis fabrication and replacements. But the high need for customized prosthesis in short period of time has challenged current technological limits. The technology needs to evolve where prosthesis can be fabricated directly from CAD file. Ability to fabricate from different materials is a challenge where biocompatible materials are required with better dimensional accuracies and mechanical properties.

5.2.1.4 Emergence

In Femur prosthesis development, any mismatch could lead to improper load distribution and discomfort. As the prosthesis requirement varies with patient and their bone quality, the design may not be sufficient. In some cases, collar is added after neck portion for suitable loading condition immediately after implantation to reduce proximal stress shielding. But the effect is dependent upon surgery. Improper calcar – collar contact after surgery may lead to heavy load in proximal zone or facture in long term. These challenges emerge upon implementation of AM product. Utilizing AM SoS, these emergent behaviors can be mitigated through various stress analysis and stress pattern studies during design. Considering, after surgery affect during design could reduce the impact on the overall system performance.

5.2.1.5 Complexity

The prosthesis development and replacement is a complex process that is influenced by various factors. External influences such as patient’s growth, bone quality, body reaction to foreign objects, surgery condition increases conflict within the system.

These factors may constrain the development of the prosthesis. The custom fit and dimensional accuracy challenge further create a complex scenario during each process. System guidance is necessary to get a solution that improves the whole system.

5.2.1.6 Uncertainty

Understanding the prosthesis requirement and possible after effect of implantation is uncertain and affects the overall system performance. Theoretical consideration increases uncertainty before and after surgery that leads to unwanted emergent behaviors. The load requirement and stress level depends upon patient's behavior and activity level that adds difficulty and complexity in various stages of prosthesis development.

5.2.1.7 Ambiguity

Lack of clarity and information transfer from one phase to another creates ambiguity on individual phase and hinders decision making ability. In case of femur prosthesis development, the length and design requirement varies with patients age and bone structure. Lack of clear knowledge and specifications differing with patient's condition cast doubts on decisions and actions. Proper guidelines and data records are needed to improve design requirements for better prosthesis development.

CHAPTER VI

SOS PRINCIPLES AND LAWS: FOUNDATION FOR THE AM SYSTEMS

The complex nature of systems and their attributes make it difficult to design, manufacture, develop and maintain the system performance. Different laws and principles are needed to accommodate these complexities in a holistic way to enhance individual system's capacity to deal with complex systems and their unique problems. After the introduction of SoS attributes, there are some set of principles that need to be taken into consideration for practitioners so that they can understand how to design manufacturing system from a more holistic perspective. These principles provide a foundation for the AM systems to improve the overall systems' performance. This section introduces some principles of complex system and provides a conceptual knowledge on how these principles are attached to each phases of AM system that guides towards system governance. The following principles are proposed as a conceptual framework that needs to be applied in additive manufacturing systems. The conceptual framework is later verified using earlier case studies.

6.1 SoS principles and laws

6.1.1 Balance of tensions

Complex systems tend to self-organize when subjected to chaos. It shows behaviors such as stable or controlled by positive feedback, unstable or controlled by positive feedback, and limited instability or tension between various forces in which it takes place [61]. The balance should be maintained between these tensions. The system should have design ranging from self-organizing to purposeful, change ranging from stability to instability and control ranging from autonomy to integration.

6.1.2 Dynamic equilibrium

Dynamic equilibrium assumes constant motion against opposing forces. The system maintains its equilibrium by adapting to forces in opposing directions. In a complex system, dynamic equilibrium supports opposing forces and creates balance between sub systems to stabilize and constantly improve. For a system to be in equilibrium all the sub systems must be in equilibrium. Also, if all the sub systems are in equilibrium, then the system must be equilibrium state maintaining a steady state.

6.1.3 Adaptation

Complex adaptive systems should have the ability to adapt through the emergent characteristics of the organization that is present within the sub systems. But not all systems have the capacity to adapt and evolve. Highly chaotic system has too few stable components that fail due to low adaptability and evolutability [62]. The systems that are poised and maintain essential variables shows adaptive behavior and have the flexibility to evolve rapidly.

6.1.4 Holism

Holism is based on the idea of a “whole” where, the whole is in the parts and the parts are in the whole reflecting a holistic character for the functions of the parts as well as of the whole [63]. Wholes are composites that have internal structure, function or character that differentiates them from aggregates or sum of parts. In a complex system, the sub systems have structure and activities that differ in character in each stage of development but the overall system or “whole” is the specific structure of sub systems with their appropriate activities and functions [63]. Therefore, complex system should be designed with the concept of holism integrating all sub systems towards a common goal.

6.1.5 Emergence

In a complex system, new model patterns appear as the consequences of systems interactions. The system tends to self-organize to accommodate these patterns and behaviors. These patterns and behaviors that arises a new, unexpected structures, properties or processes in a self-organizing system are emergent behaviors that have their own life, own rules, laws and possibilities [64]. The simple behavior based on a sub system can accumulate into complex global behavior that may affect the system performance.

6.1.6 Stability

The response of a system to perturbation determines the stability. Insensitive to small perturbation lead to stable motion. This tendency of the variables or components of a system to remain within defined and recognizable limits despite the impact of disturbances present regulates the stability of the system.

6.1.7 System darkness

No system or the details of its components and interactions can be ever completely known. Each sub system has their own responsibility and requirements towards system goal. Each detail on the sub system process is not fully known as a whole along with their interaction with other sub systems. Besides direct interactions, there are many in direct interactions between sub systems that affect the whole. Systems knowledge is never complete and accrues overtime.

6.1.8 Dialectic

Dialectic principle contains the contradicting elements: thesis or antithesis, that are resolved through integration, which over time will face a new challenge [65]. It is the process of either detecting and correcting errors and staying with the current system design through compliance or restructuring the system design by questioning the system.

6.1.9 Satisficing

Satisficing principle is the decision process such that one chooses an option that is good enough for the overall system rather than best for one sub system. It is a theory of choice where all the alternatives are examined and assessed, and decisions are made using heuristic rules to identify promising alternatives at the highest systemic level that contradicts with optimization theory [66]. Thus, a system must be designed utilizing all alternatives that satisfies the system requirements rather than individual sub system optimization.

6.1.10 Consequent production

A system can only produce what it can in terms of structure, behavior, performance. Therefore, the structure, behavior, performance of a system is not understood in terms of design or intention but on what is produced such that viability is maintained. Production provides accurate information to understand the overall system as it produces only what it can, nothing more or nothing less.

6.1.11 Genesis of structure

Designing a complex system requires proper flow of information within. Regularity of communication among system elements creates a proper system structure. Any origination of communication, whether or not anticipated or desirable, if maintained properly leads to the genesis of social structure [67]. The speed of genesis increases with the complexity of communications, number communicating, and length of time for the process.

6.1.12 Sub optimization

If each sub system is optimized with maximum efficiency, then the overall system will not operate with utmost efficiency. The low level sub optimization criterion is not good enough and effects must be assessed at least for the next higher level. The optimization of one sub system may not necessarily favor rest of the sub systems' goals depending upon the optimization criteria.

6.1.13 Boundaries

Each system has a set of boundaries that indicates some degree of differentiation between what is included and excluded in the system. The nature of boundaries can take various forms. Internal boundary creates excellence and features resistance, while external boundary encourages synergies by constructing the unified system.

These are some of the system principles that can be applied to architect a complex manufacturing system (AM system) in a holistic way to achieve a common goal of improved system performance. A conceptual framework has been developed employing these principles with the different phases of AM system as shown in figure 6.1. Each principle is linked to the AM phases that needs to be considered while developing a system framework. The two case studies summarized above are used to further evaluate the system principles and the conceptual framework.

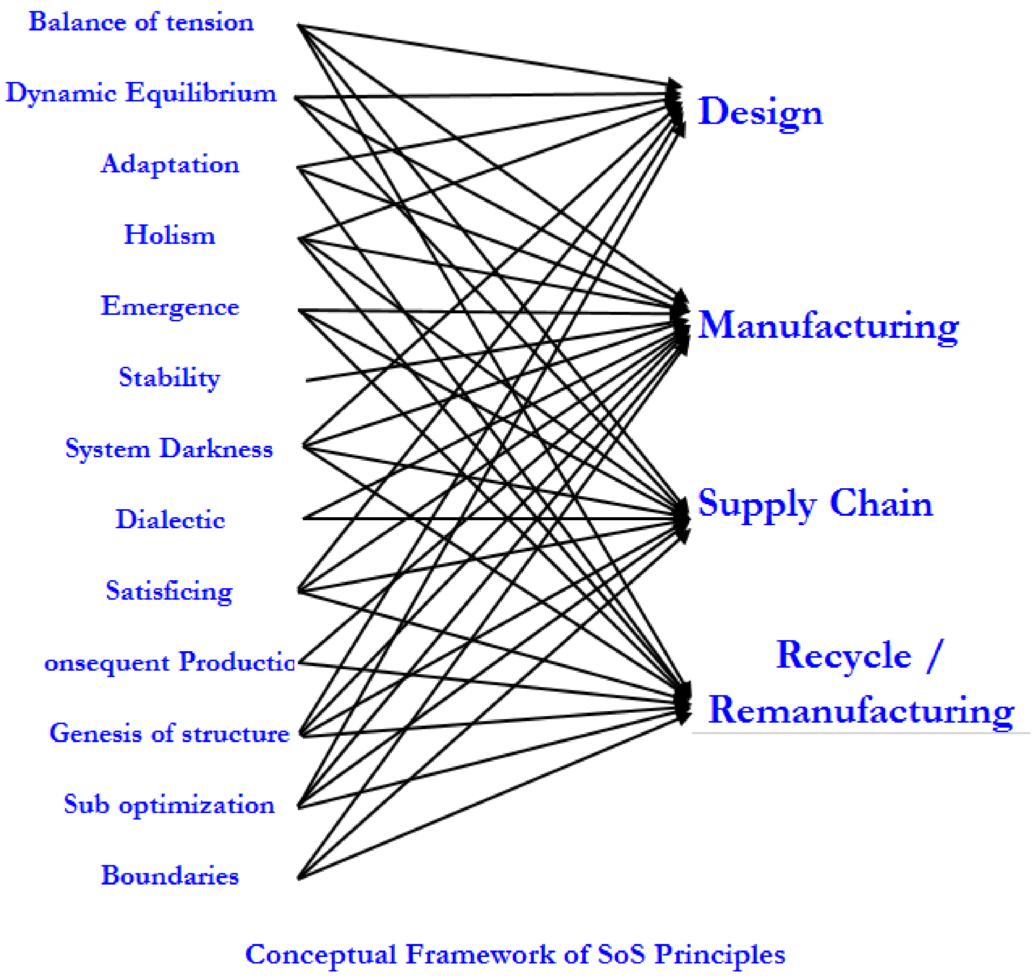

Figure 6.1 Conceptual framework of system of systems (SoS) principles

A conceptual framework showing SoS principles that corresponds to the different phases of AM system

The conceptual systems principle framework modeled in fig 6.1 shows how they are related to each phase of the AM system. Among the principles six of them are related to all phases of AM system. Balance of tension, holism, system darkness, satisficing, genesis of structure and sub optimization principles are required in all phases. System principles such as dynamic equilibrium, adaptation can be considered for design phase. Similarly, dynamic equilibrium, adaptation, emergence, stability, dialectic, consequent production and boundaries principles can be used to design the manufacturing phase of the system. Emergence, dialectic, and boundaries principles can be used for logistics phase. Also, Adaptation, emergence, consequent production, and boundaries principles impact on the recycling / remanufacturing stage.

6.2 Case study I

In the case study of air cooling ducts, there is a need to balance the tension between supply chain structure and manufacturing patterns. The interconnected and conflicting perspective centralized vs distributed production pattern should be analyzed during system design to have purposeful outcome and phases integrated towards same goal. The concept of holism where design of air ducts, their manufacturing, supply methods and remanufacturing capability should be considered and optimized towards the system goal of reduced production cost and short planes manufacturing cycle time. Despite the integration and holism, not all details are known in each phase leading to system darkness. Manufacturing may not know the challenges during design stage for machine requirements but both phases work towards system optimization with the help of better information infrastructure. Proper flow of information from naval bases to the production facilities and vice versa improves system performance by reducing any delays or aircraft downtimes. Feedbacks from supply chain and remanufacturing can be utilized in product design and manufacturing. In fact, proper genesis of structure provides the system information on sub system optimization that can be utilized to establish a satisficing criterion for holistic approach. To satisfy this condition another principle satisficing is necessary. Although distributed production is cost effective and beneficial, considering current AM technology and machine acquisition cost centralized production is viable to reduce the overall cost and optimize the system capacity. Therefore, naval air stations and master jet bases are being supplied from a single production facility in the southwest of US [51]. In the design phase of air cooling ducts, dynamic equilibrium must be maintained between the part design and its effects on other phases. The design should adapt and evolve to maintain the stability within the system. With increasing demand, the production capacity of AM machine may not be enough. This could lead to aircraft downtime and other emergent characteristics. Design with manufacturing ease may be done to reduce fabrication time and improve production rates keeping balance between design function and production capability. As technology grows, the cost of machine acquisition decreases, the production pattern needs to be changed to distributed to benefit the system. With increase in machines, production facilities and automation, the system boundary widens and emerges with new production pattern allowing efficient and effective production and distribution of spare parts. The capacity utilization lowers from 95% to 25% providing flexibility to adapt demand fluctuations and ability to remanufacture or recycle parts at the nearest production facilities [51].

CHAPTER VII

CONCLUSION

AM technology have developed and advanced from rapid prototyping to rapid manufacturing and has exhibit great application potential and advantages in aerospace, biomedical, automotive and other applications. With growing AM technology lies many challenges and limitations that needs to be addressed on a systemic level to improve the overall performance of the whole system. The concept of system of systems provides a new way of thinking that is based on holistic approach. It provides a high level viewpoint and explains the interaction between each independent sub systems. SoS can be used to address the complexity of modern manufacturing by combining all the subsystems and analyzing them as a single holistic system. It also provides a new ‘systemic’ way in improving performance and reducing overall manufacturing cost by integrating different AM life cycle phases such as design, material, manufacturing, logistics and recycling.

This conceptual research paper has introduced the system of systems concept in the area of additive manufacturing to provide a foundation for system thinking in a complex system. The rapid growth and proliferation of information within the AM system has led to a complex manufacturing environment where different phases interact to achieve better system performance and lower overall lifecycle cost. This paper presented the overview concept of SoS paradigm by introducing SoS perspective and its characteristics on the design, manufacturing, supply chain and recycling phases of AM system. Some key SoS principles and laws have been discussed that needs to be taken into consideration for practitioners in order to design the AM system from a more holistic perspective. The purpose of this SoS approach in AM system is to achieve overall optimization or ‘satisficing’ performance instead of local sub-system optimizations.

These complex system attributes and SoS principles can provide a foundation for future research. A potential application of this concept would be the

a) Development of rigorous information-infrastructure system that consists of rigorous communication channels to improve the flow of information within the AM systems, and enhance better design, integration, and analysis through a holistic system of systems engineering approach.
b) Analyzing overall AM life cycle cost compared to traditional manufacturing method utilizing SoS knowledge and principles.
c) Utilize SoS approach to evaluate overall energy utilization and other aspects of AM system.

CHAPTER VIII

FUTURE POTENTIAL

The SoS engineering perspective can be studied further to develop a rigid information infrastructure system for AM system. The information-infrastructure system can (1) provide a purposeful and delineate communication arrangement between manufacturing life cycle phases to achieve a more flexible and designable design, (2) provide a feed forward and feedback loops to ensure response to internal and external shifts as well as revised trajectory. This SoS information-infrastructure system consist of different communication channels that are connected to all manufacturing phases in a systemic way. The communication channels show the flow and processing of information within and external to manufacturing system, that provides for consistency in decision, and actions made with respect to the overall manufacturing cost. For instance, to avoid high transportation or recycling cost within the supply chain, the communication channels will provide cost-effective strategies that control the overall supply chain cost early in the design stage. The communication channels provide each phase with specific objective that help attain an effective overall manufacturing cost, early in the design phase (See Figure 8.1). Using these interrelated paths in the overall AM system, the design phase looks to achieve optimal design based on the integration of all phases throughout the communication channels. The manufacturing phase look towards continuous maintenance of the system integrity while the logistics phase aims for utilization of resources based on communication channels. At the end, the recycling phase provides a feedback loop for design development and improvement. Thereby, all the sub systems or phases are connected effectively towards improving the overall system performance.

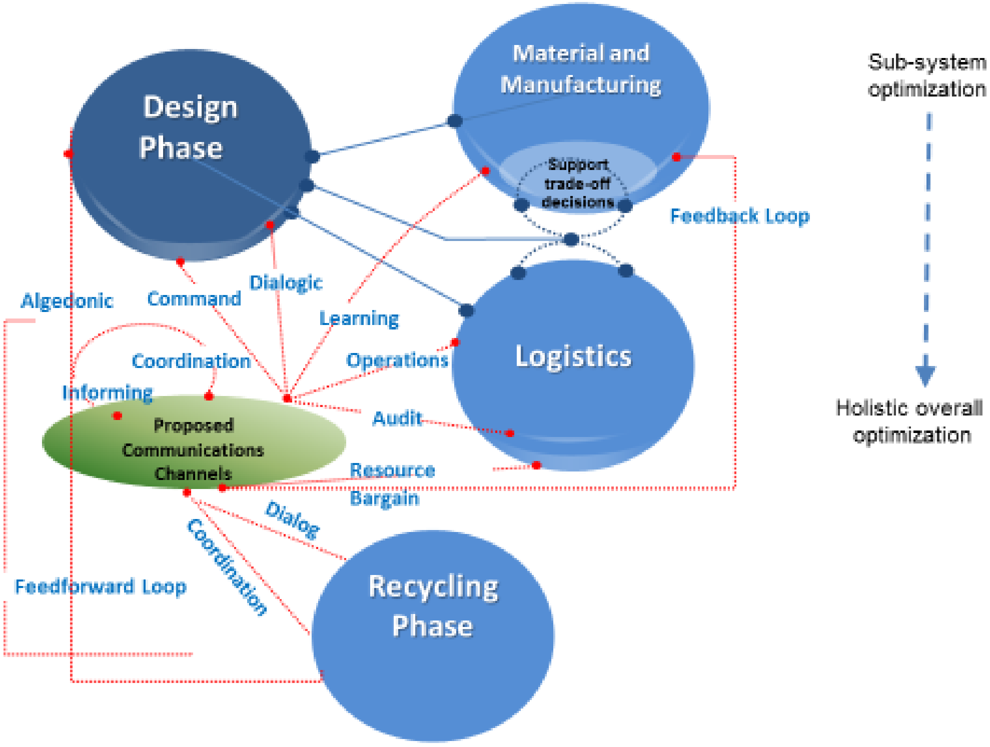

Figure 8.1 Information infrastructure system using SoS approach

Potential future research application of developing an information infrastructure system consisting communication channels

The proposed communication channels consist of initializing, control, execution, assessment, integration of all stages and communication channels. A current state of system development is established in the initial path. Control provides direction based on the information generated from the communication channels for effective design and facilitate in designing a flexible CAD file based on the information. Third path is execution where, manufacturing process parameters are designed and monitored that provide optimal design to minimize the overall cost throughout the phases. Next path is assessment where design and testing are done for the integrated phases to identify areas for necessary changes to avoid unnecessary costs in logistics and recycling phase. On next path, the later three paths are integrated to achieve a common and optimal flow. Next path consists of communication channels help consolidate all the phases of manufacturing.

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