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Systems theory as the foundation for advanced manufacturing management

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Abstract: The development of any field relies on a consistent conceptual foundation. This foundation serves as a reference framework that can inform field development while guiding practice. For Advanced Manufacturing Management we propose that Systems Theory offers such a reference framework capable of grounding field development, providing a consistent language, and guiding enhanced practice. In this article, we focus on three central points. First, we briefly examine the distinction between the Advanced Manufacturing Technologies (AMT) and Advanced Manufacturing Management (AMM) problem domains. Our focus is to suggest the special demands of the AMM domain in contrast to traditional AMT. This distinction calls for a different conceptual foundation to enable an alternative level of thinking, decision, action, and interpretation appropriate for the AMM problem domain. Second, the essence of Systems Theory is examined as an appropriate conceptual foundation for AMM. Third, we explore the implications of several key propositions from Systems Theory for the AMM field and practitioners. The article concludes by suggesting a path forward for the incorporation of Systems Theory for advancing AMM.

Keywords: AMM; AMT; axiomatic; systems theory; VUCA

1. Introduction

Advanced Manufacturing Management (AMM) continues to emerge as a field of study and an approach to address complex problems in modern manufacturing [2,10,30,29,37,46,47]. Amidst increasing ambiguity, complexity, emergence, interdependence, and uncertainty, AMM seeks to increase the probability of achieving and maintaining higher levels of desirable manufacturing system viability and performance amid internal enterprise flux and external environmental turbulences. Specifically, current modern society is faced with increasing realities of the need for developing new thinking and corresponding action. The reality of this problem domain is challenging the most central institutions necessary for society to function effectively, manufacturing included. This problem landscape has been previously summarised in several works [26,33,34,31]. For manufacturing, this reality entails:

- Ambiguity–an increasing lack of clarity in understanding/interpretation of both manufacturing systems and the context within which they exist.
- Complexity–manufacturing systems are so intricately interconnected to other systems that complete understanding, prediction, control, or explanation is impossible.
- Emergence–the unpredictability of events and manufacturing system (and other system of systems) behaviors from constituent elements, known and experienced after they occur, without the possibility for prediction.
- Interdependence–mutual influence among manufacturing systems (and other system of systems) through which the state of each system influences, and is influenced by, the state of interrelated systems.
- Uncertainty–the incomplete knowledge of manufacturing systems (and their interactions and behavior) casting doubt on decision/action consequences.

Modern complex manufacturing systems, their associated problems, and the conditions that mark their problem domain are not going away. Nonetheless, practitioners (*i.e.*, designers, owners, operators, and performers) facing this domain are left in a precarious position. They must mount an effective response to develop systems and resolve problems within the domain, without the luxury of waiting for more effective support that lies 'just' beyond the horizon. We suggest that effectiveness in dealing with modern complex manufacturing systems and their problem domain beckons for two essential ingredients. First, individuals and organizations must be capable of engaging in a different level of systemic thinking, decision, and action. This will permit more effective utilization of existing resources, including methods, tools, and techniques. Second, there is a need to develop more effective systems-based approaches (methodologies), supporting methods, tools, and techniques to address the range of complexities practitioners face more holistically.

AMM is a developing field designed to mount a better response to this state of complex manufacturing systems and their problem domain. AMM is focused on enabling practitioners to better diagnose and effectively respond to deeper-level systemic issues that impede manufacturing system performance. Thus, AMM is developing to identify and 'holistically design through' fundamental system issues. Unfortunately, these issues exist at deep tacit levels and appear only as symptomatic at the surface [27,34]. Efforts to address these problems at the surface level, although providing temporary 'fixes', will continually fail to resolve the deeper fundamental issues in modern complex manufacturing systems.

In response to the complex manufacturing systems landscape, the common thought strategies, although attaining past successes, are not appropriate to address present and future complex manufacturing system issues. Among these 'status quo' strategies are:

- **Treatment of complex manufacturing systems as simple systems:** While the complexity of systems has continued to rise exponentially, so too has the desire to 'reduce' them under the false assumption that this will permit them to be more effectively addressed. Treating complex systems as simple systems is fraught with problems [36]. This can result in oversimplification of complex systems and their problems or as Mitroff (1998) suggests, the result is solving the wrong problem precisely in the most efficient way possible.

- **Process and event-centric focus:** One strategy frequently deployed to engage, and 'tame', complex systems is through the establishment of standardized and repeatable processes and events. Emphasis on processes and events strategies falls short in the treatment of complex manufacturing systems. There simply is no degree of process or corresponding events that can substitute for understanding the purpose, function, organization, and operation of a complex system. Processes will always fall short of achieving systemic integration. In this sense, a process-based strategy is a reductionist treatment of complexity.
- **Complication as an approach to deal with complexity:** The original intent of many systems is to provide a streamlined approach to support the effective resolution of a problem or fulfillment of a need. However, in practice, this resolution is often conveyed as adding more processes, procedures, requirements, and regulations. All of these, are well well-intentioned as means to achieve mastery over complexity. Unfortunately, addressing complexity with overcomplication is ineffective, introducing constraints that can diminish system performance.
- **Over emphasis of output over outcome:** Outputs from a system are those tangible, verifiable, and objective elements that serve as products that provide value consumed external to the system. This output mindset provides the basis for a worldview (the system of values and beliefs through which all that is sensed is processed) which translates into the design, execution, and development of a system. For example, many systems focus on performance of cost, schedule, and technical achievement. After all, these attributes are objectively measurable. However, these indicators are 'systemically' limited in their measuring the value of a system. Indicators of cost, schedule, and performance are necessary for system performance. However, these indicators by themselves are sufficient indicators of a complex manufacturing system's performance. Instead, more appropriate for consideration is 'outcome', which is concerned with the utility of the manufacturing system complex. In effect, outcomes measure to what degree a system fulfills a need or effectively resolves a problem.
- **Global control as a goal:** From a systems perspective, control is about providing constraint of a system only to the degree to which is necessary to assure continued performance [32]. The excess constraint in a system (control) wastes resources and limits local autonomy (*i.e.*, independence for decision, action, and interpretation). The common manifestation of excessive global control is what has been described as overregulation, bureaucracy, and excessive constraint without evidence of commensurate value added to the system.

Given this set of circumstances, we offer three critical points. First, the present approaches do not appear to account for the changing landscape of complex manufacturing systems. This does not disparage methods, tools, or technologies to deal with present and future complex systems. However, realistically, we are not at a point where repeatable 'success' in response to this landscape can be claimed. Typical responses (*e.g.*, control) have not been shown to effectively neutralize negative consequences stemming from the landscape.

Second, the complex manufacturing systems landscape includes both 'social' and 'technical' perspectives. A technical perspective manufacturing systems is 'hard' in that it focuses on technical and objectively verifiable issues while a social perspective manufacturing systems is 'soft' in that it focuses on the nontechnical and subjectively verifiable issues. There is a propensity to lean toward technical (*i.e.*, technology-only) which fails to address the spectrum of issues beyond the technology/technical perspective, irrespective of the more complex and holistic nature of our manufacturing systems and their problems. A consideration of both the 'socio' and 'technical' dimensions of increasingly complex manufacturing systems and problems is essential to increase effectiveness [13,14,16]. Increasing interconnectedness, complexity, and uncertainty demand a different mindset and corresponding approaches to effectively deal with the present and future state of complex systems. This view aligns with the National Academy of Engineering's (1982) perspective on manufacturing systems, where, operations take center stage but with consideration of overlapping and interacting with administration and management, the product and process engineering activities, the applied sciences, and the marketing, sales, and service activities. Moreover, the overlapping and interacting includes customers for the products or services, the vendors and suppliers that provide materials, components, and services to the enterprise, the community in which the enterprise exists, and the government that establishes regulations, rules, and opportunities for the enterprise (National Academy of Engineering, 1992).

Third, there is an increasing urgency to find better ways to embrace volatility, uncertainty, complexity, and ambiguity in the landscape of complex manufacturing systems that are resistant to traditional approaches. New approaches must appreciate the volatility, uncertainty, complexity, and ambiguity nature of the emerging landscape. This will require new and novel approaches based on an underlying paradigm shift. Table 1 articulates the differences between traditional manufacturing and advanced manufacturing.

Table 1. The differences between traditional manufacturing and advanced manufacturing.

Focus Areas	Traditional Manufacturing	Advanced Manufacturing
Production strategy	Mass production	Customization and customer-focused
Organizational structure	Hierarchical	A flat, open flow of information
Labor Supply Criteria	Abundant labor supply	Skilled/technical labor available
Skills Required	Unskilled and semi-skilled	Semi-skilled and technical skills
Education	On-the-job-training. High school/vocational school	Technical degree from college/university
Production Technology	Low level (*e.g.*, casting, welding, molding, brazing, machining, *etc. etc.*)	High-level (*e.g.*, additive, and rapid manufacturing: 3-D printing, powder bed, material deposition, *etc. etc.*)
R&D/Innovation	Investment into production	Re-invest revenues into R&D
Energy	Low-cost	Low-cost, highly dependable
Infrastructure Requirements	Space	IT/digital infrastructure
Logistics	Highway and/or rail accessibility	Global supply-chain management

A key difference between Traditional Manufacturing (TM) and Advanced manufacturing (AM) is in use and reliance on technology. TM can be defined as the act of converting raw materials into finished products by using manual or mechanized transformational techniques [58]. The purpose of such activities is to add value and achieve some targeted objectives. AM can be defined as a family of activities that depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or makes use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences, including nanotechnology. AM involves both new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies [47].

The relevance of technology in AM is also evidenced in the emergence of Advanced Manufacturing Technology (AMT) which encompasses the use of innovative technology to improve products or manufacturing processes that drive innovation. AMT involves (i) the classical continuum of basic manufacturing processes, which extends from make-to-order manufacturing to continuous manufacturing, and (ii) the level of integration of the overall manufacturing system [20,56,29].

However, "advanced manufacturing" is not limited to transforming resources and technologies. It encompasses a wide range of considerations, including the technical/technology, human/social, policy, political, information, and organizational/managerial dimensions. The managerial aspect of AM is where "superior management" is required (The New England Council, 2015, p. 14). However, there remains a lack of articulated superior management methods (and methodologies) for advanced manufacturing [29,30]. In the previous research, advanced manufacturing management (AMM) is introduced as an emerging field and approach for addressing the technical/technology, human/social, policy, political, information, and organizational/managerial dimensions of the modern landscape of complex manufacturing systems. AMM is provisionally defined as "innovative means to more effectively control, communicate, coordinate, and integrate technologies, methods, and processes to enhance the production of manufacturing goods and services while addressing technology (*i.e.*, hardware and software), human, social, organizational, political, and policy implications" [29]. This view of AMM shifts the focus of TM and AM in several ways (beyond technical/technology) to:

- **Manufacturing System Control.** In this case, control entails the necessary constraints to ensure consistent performance and future system trajectory. Control is not a pejorative term to be scorned as a form of domination over a particular venue, activity, or entity. Rather, manufacturing system control is essential to ensure that the system stays on the trajectory that will provide future viability in response to changing conditions and circumstances. This is achieved by providing the greatest degree of autonomy (freedom and independence of decision, action, and interpretation) possible while still maintaining the system at desired levels of performance and behavior across social and technical dimensions. In effect, this suggests that over over-constraint of a system wastes resources (constraint is not free), limits system initiative/creativity, and diverts important emphases of a metasystem unnecessarily to lower levels of the system (inefficiency).

- **Manufacturing System Communication.** In this case, communication entails the flow and processing of information necessary to support consistent decisions, actions, and interpretation across the manufacturing system, operations, and environment. Communication includes not only the exchange of information but also the interpretative schemas that permeate the system. These interpretative schemas are necessary to provide coherence in making, understanding, and interpreting the myriad of exchanges in a system. Communications may range from formal to informal, explicit to tacit, and patterned too emergent. There is not an optimal configuration for communication in a system and the arrangements are certainly subject to shifts over time and emergent patterns. Communication is something that would be better off not left to chance self-organization. Instead, purposeful design and evolution of communications within a complex manufacturing system landscape are more likely to produce and maintain desirable results.
- **Manufacturing System Coordination.** In this case, coordination entails providing effective interaction among different manufacturing systems complex within and external to the system, to prevent unnecessary oscillations. Certainly, coordination is an essential aspect to ensure that a system provides sufficient interaction among different elements to maintain consistency. Quite possibly the most important aspect of coordination is the damping of unnecessary fluctuations as the system operates. In effect, this implies that there must be sufficient standardization to provide a routine interface as well as a sufficiently robust design to absorb emergent conditions that could not have been known in advance.
- **Manufacturing System Integration.** In this case, integration entails design for system unity with common goals, accountability, and balance between individual autonomy and system-level interests. The primary focus of integration is to ensure that the system achieves desirable levels of performance (*i.e.* social and technical) while: (1) providing the maximum level of autonomy to constituents, (2) invoking the minimal constraint necessary for the system to function as a unity in achieving the intended purpose, and (3) strategically shifting the balance point between autonomy and integration based on changes in contextual factors and system performance levels. Integration is not achieved through serendipity, but rather by active design and continuous evolution.

In this view of AMM, it is necessary to evolve the current state of knowledge for AMM to include elements of design, execution, and evolution to provide control, communication, coordination, and integration of a complex manufacturing system. The design accentuates the necessity to engage a complex manufacturing system purposely and proactively. Execution is where a design meets the harsh realities of the 'real world' which is fraught with volatility, uncertainty, complexity, and ambiguous conditions that that are sure to test the most thoughtful designs. Evolution recognizes that manufacturing systems as well as their environments are in constant flux. Therefore, designs must be flexible and evolve in response to internal and external changes impacting the manufacturing system. Design, execution, and evolution are key features of AMM that shift the focus of TM and AM as indicated in Table 1. Moreover, the focus of TM and AM (*i.e.*, production strategy, organizational structure, labor supply criteria, skills required, education, production technology, research, and development (innovation), energy, infrastructure requirements, and logistics) are subsumed within elements of design, execution, and evolution. Therefore, while EM and AM focus on advanced manufacturing technologies, AMM encompasses more holistic dimensions of the complex manufacturing systems landscape, including technical/technology, human/social, policy, political, information, and organizational/managerial dimensions. Nevertheless, there remains a scarcity of development of the AMM field. In fact, while acknowledging the overemphasis on technology, Katina *et al.* [29] suggest a more balanced development of the field, inclusive of philosophical, methodological, axiological, axiomatic, and theoretical perspectives that complement the applications, methods, tools, and techniques [29,34]:

- **Philosophical development:** Development directed at establishing a theoretically strong, coherent, and articulated philosophical grounding of AMM and a foundation upon which other field developments can be consistently based.
- **Theoretical development:** development focused on explaining phenomena related to AMM and developing explanatory models and testable conceptual frameworks. The range of theoretical developments advances the understanding of the field and the phenomena of central concern.
- **Epistemological development:** Development that establishes how a system observer/owner/operator begins to understand problematic situations and communicate knowledge to fellow observers/owners/operators or observers. This dimension is focused on the form of knowledge, how knowledge is acquired, and what is 'true' or 'false' for the AMM field.
- **Ontological development:** Development that establishes how to deal with the existence of AMM entities and how such entities can be grouped based on similarities and differences. Ontology helps to describe how an observer views the nature of reality in the AMM field or how concretely the external world might be understood.
- **Axiological development:** Development that establishes the underlying value, value judgment frameworks, and belief propositions fundamental to understanding the variety of perspectives informing AMM. The absence of axiological considerations for the development of the field fails to recognize the essential value foundations upon which other development areas can utilize the foundational reference point(s).
- **Methodological development:** Development undertaken to establish theoretically informed frameworks that provide high-level guidance for the design, analysis, deployment, and evolution of AMM. Generalizable methodologies provide a transition from the conceptual foundations (philosophical, theoretical, and axiological) to applications that address AMM and its inherent issues.
- **Axiomatical development:** Development of the existing and emerging theorems, principles, and laws that define the field and constitute the 'taken for granted'

knowledge upon which the field rests. This also includes the integration of knowledge from other informing and related fields/disciplines. For example, if General Systems Theory [60] is suggested as an attempt to transcend the dynamics of a dialectical synthesis to grasp the total dynamics of reality, then it should provide axioms and supporting propositions that enable axiomatic development addressing the totality of dynamics of reality of the whole in AMM.

- **Methodical development:** Development focused on generating specific models, technologies, standards, processes, and tools for AMM. In effect, this is the development of practitioners' supporting toolsets and capabilities. While literature includes many methods and techniques for manufacturing [2], methods should be compatible with the suggested elements of conceptual foundations of AMM, including philosophical, methodological, axiomatic, and axiological predispositions. This approach encourages consistency in the development of applicable methods.
- **Application development:** Development emphasizing the advancement of AMM practice through the deployment of conceptually sound technologies and methods. This area must address emerging technologies (*e.g.*, Artificial intelligence, Blockchain Technology, Cloud Manufacturing, Intelligent Manufacturing, Internet-of-things-enabled manufacturing) as well as emerging threats and risks [10]. Applications that are not rooted in the conceptual foundations of the field are not likely to be either consistent or conceptually congruent with the deeper underpinnings upon which the field rests. As such, applications, void of the field's philosophical, theoretical, and axiomatic foundations, are not likely to produce the intended utility for which they have been designed.

The present research addresses axiomatical developments for AMM. Specifically, the goal is to ground AMM in the axioms and the supporting propositions of Systems Theory [1] to provide a strong starting point for further axiomatic development of the field. The remainder of this paper is organized as follows: Section 2 introduces Systems Theory as a foundation for understanding complex manufacturing systems and their landscape. Section 3 explores the implications of several key propositions from Systems Theory for the AMM field and practitioners. Section 4 provides a conclusion offering several challenges for the incorporation of Systems Theory for advancing AMM.

2. Systems theory as the foundation for advanced manufacturing management

In the traditional scientific method, complex organisms are nothing more than the sum of their parts. This suggests that a complex organism can be reduced to constituent elements [21,61]. However, as doubts regarding this thinking emerged, researchers became more interested in notions of a Holon—a totality, as suggested by von Bertalanffy [62]. Concisely, von Bertalanffy [62] suggested that "…since the fundamental character of the living thing is its organization, the customary investigation of the single parts and processes cannot provide a complete explanation of the vital phenomena. This investigation gives us no information about the coordination or parts and processes." This movement started the search for a general systems theory. There are three related, but different terms associated with the search for General Systems Theory (GST): systems science, systems technology, and systems philosophy.

Systems science emphasizes the "scientific exploration and theory of 'systems' in various sciences (*e.g.*, physics, biology, psychology, social sciences), and general systems theory as the doctrine of principles applying to all (or defined subclasses of) systems" [62]. This aspect of GST deals with knowledge of the connected 'wholes' as opposed to detailed and isolated systems. Systems Technology is the aspect of GST dealing with "problems arising in modern technology and society, including both 'hardware' (control technology, automation, computerization, *etc. etc.*) and 'software' (application of systems concepts and theory in social, ecological, economical, *etc. etc.*, problems)" [62]. In this view of GST, the assumption is that solving the world's most pressing issues (*e.g.*, pollution, economies, healthcare, and international conflicts), cannot be done in isolation from one another [57,62,66]. Arguably, the increasing levels of volatility, uncertainty, complexity, and ambiguity (VUCA) associated with the operating landscape in the 21st century confirm this dilemma. Consequently, the systems technology element of GST is concerned with the development of unique sets of methods and tools enabling the discovery of problematic situations, understanding, and bringing about positive change.

The third element of GST is *systems philosophy*. In this case, philosophy addresses the philosophical underpinnings (*i.e.*, paradigm) within which GST rests. These underpinnings include (i) systems ontology, (ii) systems epistemology, and (iii) the nature of man. *Systems ontology* deals with how an observer views reality. In this case, reality can be characterized along two opposing extremes: realism and nominalism. Realism is focused on reality being described as independent of the observer. In principle, every person can verify every aspect of the objective reality. Anything that cannot be verified in this way is not part of the objective reality. Nominalism is rooted in the notion that reality is a 'construction' of the observer and thus does not exist independently of the observer. In principle, every person's 'truths' are subjective and depend on 'personal experiences.' Epistemology deals with how people obtain and communicate knowledge. Again, two opposing characterization is used: positivism and anti-positivism. Positivistic epistemology holds that knowledge is objective, reducible, and concrete. In contrast, anti-positivistic epistemology holds that knowledge is subjective, irreducible, and fallible. The third element of systems philosophy addresses the nature of human beings. On the one hand, people are viewed as deterministic suggesting a predetermined outcome, deducible from the cause-effect relationship. On the other, people are viewed as voluntaristic, suggesting that people have 'free will' with respect to determining relationships that exist beyond predetermined outcomes or absolute cause-effect relationships.

The proceeding discussion is meant to highlight the unique background of GST and how it might be used to offer alternative insights into our phenomenon (including manufacturing systems) and their operating environment. GST is fundamentally different along with elements of systems science, systems technology, and systems philosophy. Furthermore, although GST was initially developed in mathematical terms and emphasized isomorphic relationships [61], it was observed that much of von Bertalanffy's writing reflects a deeper concern with the mechanistic and reductionist orientation of then-current models in biology and psychology [21]. This is supported by the work of von Bertalanffy [62] who later stated that "classical science in its various disciplines, such as chemistry, biology, psychology, or the social sciences, tried to isolate the elements of the observed universes…We have learned, however, that for an understanding not only the elements but their interactions as well are required – say, the interplay of enzymes in a cell, the interactions of many conscious and unconscious processes in the personality, the structure and the dynamics of social systems, and so forth".

A single and universally accepted GST has yet to emerge. However, it is well established that "some of the concepts and insights of one discipline [can] contribute to the problems and theories of another" [57]. Additionally, the aspect of GST describing isomorphic concepts, laws, principles, and theorems applicable to different systems is evident in literature [1,17,19,27,28] . For example, in the work of Adams *et al.* [1] and Whitney *et al.* [68], thirty (30) propositions (see Table 2) - inclusive of laws, principles, and theorems – are proposed as means to investigate situations from a systems viewpoint along seven (7) axioms (*i.e.*, centrality, context, design, goal, information, operational, and viability). Furthermore, over 80 principles can be attributed to GST [27]. In this instance, Strijbos' work supports the notion that systems theory is about how different theoretical perspectives can be transported from one field to another to address a wide range of issues in distinctive disciplines. This was the case in control engineering which had roots in cybernetics [25,57,61]. It is from this perspective that this research uses Systems Theory as suggested by Adams *et al*.[1]: "a unified group of specific propositions which are brought together to aid in understanding systems, thereby invoking improved explanatory power and interpretation with major implications for systems practitioners" [1].

The Centrality Axiom stipulates that central to all systems are two pairs of propositions: emergence (and hierarchy) and communication (and control). The associated propositions describe the system by focusing on (1) a system's hierarchy and its demarcation of levels based on emergence and systems control which requires feedback on operational properties through communication of information.

The Contextual Axiom states that the meaning of a given system is informed by the circumstances and factors that surround the system. The associated propositions are those that bind the system by providing guidance that enables an investigator to understand the set of external circumstances or factors that enable or constrain a particular system.

The Design Axiom states that system design is a purposeful imbalance of resources and relationships. Resources and relationships are never in balance because there are never sufficient resources to satisfy all the relationships in a systems design. The design axiom guides how a system is planned, instantiated, and evolved in a purposive manner.

The Goal Axiom states that systems achieve specific goals through purposeful behavior using pathways. The associated propositions address the pathways and means for implementing systems that can achieve a specific purpose.

The Operational Axiom states that systems must be addressed *in situ*, where the system is exhibiting purposeful behavior. The associated propositions address the system *in situ*, where the system is functioning to produce behavior and performance.

The Information Axiom states that systems create, possess, transfer, and modify information. The information axiom provides an understanding of how information affects systems.

The Viability Axiom states that key parameters in a system must be controlled to ensure continued existence. The viability axiom addresses how to design a system so that changes in the operational environment may be detected and affected to ensure continued existence.

Table 2. A contemporary view of systems theory.

Axiom	**Associated principles and proponents**	**Description of principles**
Centrality	Communication [49,50]	In communication, the amount of information is defined, in the simplest cases, to be measured by the logarithm of the number of available choices. Because most choices are binary, the unit of information is the bit or binary digit.
	Control [12]	The process through which a whole entity retains its identity and/or performance under changing circumstances.
	Emergence [12,3]	Whole entities exhibit properties that are meaningful only when attributed to the whole, not its parts. Every model of systems exhibits properties as a whole entity that derive from its component activities and their structure but cannot be reduced to them.
	Hierarchy [12,45]	Entities meaningfully treated as wholes are built up of smaller entities which are themselves wholes . . . and so on. In a hierarchy, emergent properties denote the levels.
Context	Complementarity [8,39]	Any two different perspectives or models about a system will reveal truths about that systems are neither entirely independent nor entirely compatible.
	Darkness [5,15]	Each element in the system is ignorant of the behavior of the system, it responds only to information that is available to it locally. This point is vitally important. If each element 'knew' what was happening to the system, all the complexity would have to be present in that element.
	Holism [55]	The whole is not something additional to the part: it is the parts in a definitive structural arrangement and with mutual activities that constitute the whole. The structure and the activities differ in character according to the stage of development of the whole, but the whole is just this specific structure of parts with their appropriate activities and functions.
Design	Minimum critical specification [13,14]	This principle has two aspects, negative and positive. The negative aspect of the principles states that no more should be specified than is essential for design; the positive aspect of the principle requires that we identify what is essential for design.
	Pareto [44]	In any large complex system, eighty percent of the outputs or objectives will be produced by only twenty percent of the system means.
	Requisite Parsimony [40,54,67]	Human short-term brain activity (memory) is incapable of dealing with or recalling more than seven plus or minus two items.
	Requisite Saliency [9]	The factors that will be considered in a system design are seldom of equal importance. Instead, there is an underlying logic awaiting discovery in each system design that will reveal the saliency of these factors.
Goal	Equifinality [59]	If a steady state is reached in an open system, it is independent of the initial conditions and determined only by the system parameters (*i.e.* rates of reaction and transport). Hence, taking different paths, the same final state may be reached from different initial conditions.

Table 2. *Cont.*

Axiom	Associated principles and proponents	Description of principles
Goal	Multifinality [10]	Radically different end states are possible from the same initial conditions.
	Purposive Behavior [48]	Purposeful behavior is meant to denote that the act or behavior may be interpreted as directed to the attainment of a goal to a final condition in which the behaving object reaches a definite correlation in time or space with respect to another object or event.
	Satisficing [52,53]	The decision-making process whereby one chooses an option that is, while perhaps not the best, good enough.
	Viability [7]	A function of balance must be maintained along two dimensions: (1) autonomy of subsystem *versus* integration and (2) stability *versus* adaptation.
Information	Redundancy of Potential Command [38]	Effective action is achieved by an adequate concatenation of information. In other words, power resides where the information resides.
	Information Redundancy [51]	Errors in information transmission can be protected against, to any level of confidence required, by increasing the redundancy in the messages.
Operational	Dynamic Equilibrium [18]	For a system to be in a state of equilibrium, all subsystems must be in a floating (not steady or stable) state characterized by invisible movements and preparedness for change equilibrium. All subsystems being in a state of equilibrium, the system must be in equilibrium.
	Homeorhesis [64,65]	The concept encompasses dynamical systems that return to a trajectory, even if disturbed in development. In homeorhesis, systems return to a particular path of a trajectory while in homeostasis systems return to a particular state.
	Homeostasis [11]	The property of an open system is to regulate its internal environment to maintain a stable condition, through multiple dynamic equilibrium adjustments controlled by interrelated regulation feedback mechanisms.
	Redundancy [43]	These are the means of increasing both the safety and reliability of systems by providing superfluous or excess resources usually in the form of backup or fail-safe.
	Relaxation Time [24,23]	Systems stability is possible only if the system's relation time is shorter than the mean time between disturbances.
	Self-organization [4]	Complex systems organize themselves; they exhibit the emergence of global structures and behaviors out of interactions of local parts.
	Sub-optimization [22]	If each subsystem, regarded separately, is made to operate with maximum efficiency, the system will not operate with utmost efficiency.
Viability	Circular Causality [63]	Any effect becomes a causative factor for future effects, influencing them in a manner particularly subtle, variable, flexible, and of an endless number of possibilities.
	Feedback [69]	All purposeful behavior may be considered to require negative feedback. If a goal is to be attained, some signals from the goal are necessary at some time to direct the behavior.
	Recursion [7]	If a viable system contains a viable system, then the organizational structure must be recursive; in a recursive organizational structure, any viable system contains and is contained in, a viable system.
	Requisite Hierarchy [6]	The weaker on average the regulatory abilities are and the larger the uncertainties of available regulators, the more hierarchy is needed in the organization of regulation and control to attain the same result, if possible.
	Requisite Variety [5,19]	The control achieved by a given regulatory sub-system over a given system is limited by: 1) the variety of the regulator and 2) the channel capacity between the regulator and the system.

In this section, Systems Theory is introduced as a foundation for understanding complex manufacturing systems and their landscape. More specifically, we suggest that Systems Theory can serve as the basis for axiomatical developments of AMM. Systems Theory provides a robust conceptual foundation that when projected to AMM, can influence the design, execution, and development of the field. Based on several articulations [1,68,32,35], at a basic level Systems Theory can be understood as a set of *axioms* (*i.e.*, truths about manufacturing systems that are accepted without need for justification) and *propositions* (*i.e.*, a collected set of laws, principles, and theorems explaining structure, behavior, and performance of manufacturing systems and their phenomena). Therefore, this view of Systems Theory suggests several central tenets concerning the capacity to deal with the current manufacturing landscape marked by volatility, uncertainty, complexity, and ambiguity (VUCA)–all which impact manufacturing systems—among these tenets, we include:

- Manufacturing system behavior, structure, and performance result from the interactions among the system elements/entities.
- Holism invokes understanding at the level of the 'whole manufacturing system' which cannot be deduced from the individual elements/entities – system-level properties, behavior, and performance emerge from interactions between system elements.
- As mentioned above, Systems Theory consists of a set of axioms and propositions that explain manufacturing system behavior and performance.
- Without exception, all manufacturing systems are subject to the axioms and propositions which constitute Systems Theory.

3. Implications of systems theory propositions for advanced manufacturing management

In the preceding section, the body of knowledge for Systems Theory is organized into a set of 7 axioms and 30 associated propositions. Table 3 explores the implications of several key propositions of Systems Theory for the AMM field and practice. The complete articulation of this set is beyond the scope of the present research.

Table 3. Systems theory implications for AMM Field.

Systems Theory Proposition	Implications for AMM Field
Communication	AMM development advocates for communication as a critical element in the manufacturing system. The field recognizes the role of the flow (*i.e.*, the transmission of information within the system) and interpretation (*i.e.*, actionable information that supports consistency in understanding) in the manufacturing life cycle.
Control	AMM development supports the need for the establishment of control requirements that regulate capacity and constraints on manufacturing design and execution. System control is essential to ensure the continuing axiomatical development of advanced manufacturing systems. Control ensures the minimal constraint of autonomous subsystem while ensuring integration of the whole system.
Emergence	AMM development advocates for emergence that results in patterns, behavior, or performance in complex manufacturing systems resulting from their operation. This cannot be predicted in advance, even more so due to volatility, uncertainty, complexity, and ambiguity. AMM axiomatical development is subject to emergence.

Table 3. *Cont.*

Systems Theory Proposition	Implications for AMM Field
Complementarity	AMM development advocates for multiple different viewpoints and perspectives. There is always a logic and corresponding set of assumptions that make alternative viewpoints correct. We can enhance our understanding of manufacturing systems by understanding and challenging divergent logic/assumptions and potentially reducing unnecessary conflict.
Incompressibility	In AMM development, any representation (model) of a complex manufacturing system is based on abstractions, inevitably subject to abstraction error. Thus, the AMM axiomatical development is enhanced by accepting that manufacturing system knowledge is always incomplete, subject to interpretation, and fallible. Manufacturing system knowledge must be continually questioned for appropriateness, and we must be willing to evolve formulations based on new knowledge and interpretations.
Holism	In AMM development, manufacturing design is subject to the entire spectrum of influences, including technology, social, human, economic, organizational, managerial, policy, and political dimensions. Narrow conceptions of AMM can and should be challenged across the holistic spectrum and associated interactions.
Boundary	AMM development recognizes that system boundaries determine what is included/excluded for any manufacturing efforts and should be made explicit through criteria for inclusion/exclusion concerning the system of interest. Additionally, AMM recognizes a boundary can change over time with new knowledge and resolution of ambiguities.
Minimal critical specification	In AMM development, manufacturing system regulation reduces autonomy and can be wasteful of scarce system resources. In pursuit of excellence in manufacturing, care must be taken to constrain a system only minimally, providing only those constraints that are necessary to preserve desired outputs and outcomes.
Requisite saliency	In AMM development, all characteristics (*e.g.* design parameters for sustainability) are never of equivalent importance. Clarity for the different weightings and priorities of different factors or attributes must be addressed to provide more congruent trade-off decisions concerning the manufacturing system lifecycle.
Equifinality	AMM development must accept that there are alternative approaches (pathways and means) that can produce equivalent performance manufacturing results. It is naïve to assume that, for example, manufacturing performance, will only be achieved through one ‘optimal’ means in a complex manufacturing system.
Satisficing	AMM development practices must accept that, for complex manufacturing systems, the aim for ‘optimal’ cannot be achievable. Multiple different possibilities can achieve desirable performance. Therefore, the pursuit of optimal outcomes (or design) will only consume scarce resources that can be expended in pursuit of other pursuits.
Redundancy of Potential Command	In AMM development, decision authority should reside at the point where decision/action can best be taken in response to emergent issues. This is the point where decisions can become actionable. The farther decisions are removed in time, location, and action, the greater the possibility for reduced effectiveness in manufacturing.
Dynamic Equilibrium	AMM development must support the manufacturing capability to adjust ‘on the fly’ to changing circumstances and conditions. This is necessary to maintain stability in the face of inevitable flux in manufacturing systems and their environments.
Homeorhesis	AMM development requires constant adjustment to maintain the desired trajectory of the manufacturing system. As inevitable changes in external circumstances occur, they will require that adjustments be made. The manufacturing trajectory adjustments are best achieved through purposeful design rather than a response to change or crisis events.

Table 3. *Cont.*

Systems Theory Proposition	Implications for AMM Field
Homeostasis	AMM development supports designs that provide adjustments to assure that key (internal) parameters maintain balance in response to the inevitable internal flux that might impact the ability to achieve manufacturing objectives.
Redundancy	AMM development requires that those taking the provide the necessary mechanisms that permit the allocation of resources necessary to support sustainability goals. The manufacturing landscape is replete with volatility, uncertainty, complexity, and ambiguity that make it impossible to predict many variables (*e.g.*, performance). Therefore, it is prudent to have an excess of resources available to compensate as necessary, even under difficult circumstances and inevitable variabilities, whose specific form cannot be known in advance.
Self-organization	Self-organization permits patterns to emerge without interference (constraint) being invoked in AMM. This means that for AMM development, self-organization requires the least energy for the organization of patterns and manufacturing system structure. It is an effective approach for design if sustainability performance objectives continue to be at desirable levels.
Sub-optimization	Integration of manufacturing system elements to achieve and maintain unique capabilities beyond individual systems requires those individual systems/elements to surrender some level of autonomy in favor of integration. AMM axiomatical development should involve, by design, a balance between subsystem autonomy and system integration.
Requisite Hierarchy	Those responsible for the AMM should 'flatten' the hierarchy. This should focus on regulatory capacity being provided to assure consistent performance. Care must be taken to ensure that only the essential hierarchy necessary to maintain control of manufacturing systems is put into place.
Requisite Variety	AMM practice for sustainability must ensure that the regulatory capacity and mechanisms are sufficiently matched to that required by the environment. Lacking sufficient 'matching' variety will eventually overwhelm a manufacturing system and threaten sustainability.

AMM axiomatical development grounded in Systems Theory establishes the underlying value, value judgment frameworks, and belief propositions fundamental to understanding the variety of perspectives informing the field. From the above set of Systems Theory perspectives, there are three central themes for AMM development for practice:

Manufacturing system viability–Beer (1979) introduced viability as the ability of a system to continue existence. The maintenance of viability is required for a system to be sustainable in the long term. Viability mustn't be a 'binary', either/or proposition, that would suggest a system exists or does not exist. Instead, system viability exists over a range of existence. At the high end, viability would indicate that a manufacturing system is performing at a high level. At the low end, viability would be limited and only support a minimal existence. Thus, AMM can be thought of as promoting viability long a range based on the context of the whole manufacturing system.

- Manufacturing requisite variety–Requisite variety, following the development by Ashby (1956; 1991), requires that a system be capable of matching or exceeding the variety (*e.g.* disturbances) being generated by the environment. Variety in the environment can be thought of as the number of states that exist in the environment and might act to challenge or disturb a manufacturing system. Sufficiently matching the variety of manufacturing system relevant environments is essential to maintain the existence (viability) over time. This is particularly important as the manufacturing environment landscape of volatility, uncertainty, complexity, and ambiguity (VUCA) will continue to evolve and generate variety which must be matched by the manufacturing system's regulatory capacity to maintain sustainability.

- Manufacturing variety engineering–Concerned with the purposeful design, execution, and development of systems to provide the regulatory capacity essential to match environmentally generated variety, as well as variety generated internally to a system. If variety is not effectively absorbed, the ability of a manufacturing system to remain viable can be called into question. Thus, the establishment of manufacturing requisite variety is essential to the viability and sustainability of manufacturing systems. The engineering of variety provides the essence of maintaining viability and, for sustainability, provides for long-term continuing existence by regulating variety.

4. Conclusions and directions

AMM is provisionally defined as "innovative means to more effectively control, communicate, coordinate, and integrate technologies, methods, and processes to enhance the production of manufacturing goods and services while addressing technology (*i.e.*, hardware and software), human, social, organizational, political, and policy implications" [29]. However, the development of any field is contingent on not only the problems/needs it intends to address, but also the development across multiple strata, ranging from theory to applications. The present research has outlined the axiomatical underpinnings of AMM grounded in Systems Theory describing a set of *axioms* and *propositions* along along with key tenets concerning the capacity to deal with the current manufacturing landscape marked

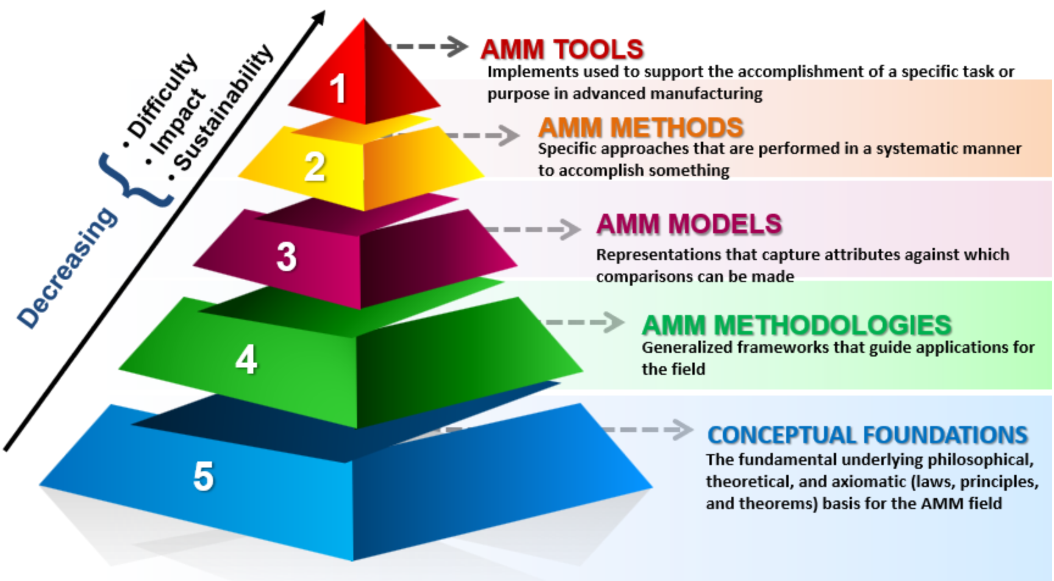

Figure 1. Possible areas of research contributions for advancing AMM.

by volatility, uncertainty, complexity, and ambiguity. This collective, axiomatical development defines the AMM field and constitutes the 'taken for granted' knowledge upon which the AMM field rests.

However, AMM axiomatical development only provides a theoretical/conceptual basis that informs the base of the field as indicated in the 'pyramid' of Figure 1.

At the lower base levels (Theoretical and Methodological) this is where AMM is grounded in Systems Theory's axioms and propositions. It is noteworthy, that AMM, whether by design, problem demand, or practitioner proclivities, has largely neglected the development of the base. While short-term success might be experienced without this 'grounding', long-term stability provided from the stable reference of the base is lost without inclusion in the field development.

We now suggest that from the strength of the underlying foundations, the building of methodologies, models, methods, and tools for the realization of practice applications of the suggested AMM axiomatic knowledge [29]. Without judgment, we would argue that AMM has been more focused on developments at the upper strata of the pyramid. Moreover, case applications, especially those that address the differences between the AMM approach and other approaches to manufacturing are more likely to enhance the tangible and intangible value of the AMM field. The grounding of AMM in Systems Theory should affect philosophical, methodological, axiological, axiomatic, and theoretical levels that complement the applications, methods, tools, and techniques used in advanced manufacturing. However, without a strong conceptual base, there can be a decreased understanding of the problem domain and, the impact of methods and tools, and as such affects the long-term viability of the field.

The following is a call for research to extend AMM research and practice. In summary, there are six essential challenges. First, manufacturing systems are subject to Systems Theory laws, principles, and theorems. Like the accepted laws of natural science (*e.g.*, gravity), manufacturing systems also have governing axions and propositions that govern their existence and behavior. The field of AMM is beholden to these propositions. System propositions are always there, non-negotiable, unbiased, and explain manufacturing system performance as well as impacts on future system sustainability. The challenge for AMM practitioners is understanding the implications of Systems Theory propositions for manufacturing system design, execution, and development. Overdependence on self-organization (*i.e.*, allowing structure and behavior to evolve without constraint) is not likely to produce the desired manufacturing system performance. There must be a balance between self-organization and purposeful design.

Second, manufacturing systems must perform essential governance functions that determine system performance. System governance functions, grounded in Systems Theory, are performed by all systems, regardless of sector, size, or purpose. These functions define 'what' must be achieved for the governance of a system. Every system invokes a set of unique implementing mechanisms (means of achieving governance functions) that determine 'how' governance functions are accomplished. Mechanisms can be formal-informal, tacit-explicit, routine-sporadic, or limited-comprehensive in nature. The challenge for AMM practitioners is articulating the governance functions in the context of the manufacturing system of interest and the ability to assess the factors enabling/constraining its viability. An imbalance in focus between the present and future of the manufacturing system can result in the sacrifice of the system in either the long term, short term, or both.

Third, the execution of governance functions generates the communication, control, coordination, and integration responsible for producing system performance. *Control* invokes the constraints which provide the regulatory capacity of a manufacturing system. These constraints should be at a minimal level while still achieving desired system performance. Thus, the autonomy (*i.e.*, freedom and independence of decision/action/interpretation) of manufacturing system constituents is preserved to the greatest degree possible. *Communication* provides for the consistent flow and interpretation of information. It supports congruence in decisions, actions, and interpretation. *Coordination* ensures that there is no excessive oscillation within the manufacturing system. Unnecessary and unproductive fluctuations are avoided through standardization, protocols, and procedures. *Integration* is focused on the achievement and maintenance of manufacturing system identity. This assures that the system is a 'unity', acting and performing, beyond that capable of individual system constituents. The challenge for AMM practitioners is understanding how system performance influences control, communications, coordination, and integration in relationship to the achievement of desired goals and objectives. For example, permitting control, communications, coordination, and integration for a manufacturing system to advance without purposeful development from a holistic view is not likely to produce the desired level of performance for a system operating under volatility, uncertainty, complexity, and ambiguity.

Fourth, the execution of governance functions, supported by associated communication channels, in accordance with Systems Theory axioms and propositions, is responsible for the level of system performance achieved and continuing system viability. Since all viable systems perform governance functions, the degree to which the functions are effectively performed will determine the performance of the system and continuing viability, which supports sustainability. Purposeful governance invokes a higher state of viability (existence) and can support an enhanced manufacturing system performance. The enhanced manufacturing system performance, including objectives is designed, executed, and evolved through governance functions. The challenge for AMM practitioners is understanding that enhanced unique capabilities beyond individual systems are achieved at the governance level despite volatility, uncertainty, complexity, and ambiguity. For example, all complex systems perform governance functions and communication channels, irrespective of whether they are acknowledged. Acknowledgment of the functions and channels, coupled with their active development, provides a substantial step forward in propagating sustainable manufacturing systems.

Fifth, there are performance consequences for violating Systems Theory propositions in the execution of manufacturing systems. Regardless of knowingly, or unknowingly, violating system propositions there will be consequences. This will ultimately impact the expected system performance. In the best case, violations can result in degraded performance and hinder the achievement of capabilities beyond individual systems. In the worst case, the violation can escalate to cause catastrophic consequences, even eventual manufacturing system collapse. The challenge for AMM practitioners is developing a capability to identify and trace systems performance variabilities to violations of Systems Theory propositions. For example, understanding the violation of a system proposition, such as control (provision of constraint necessary to maintain system performance), will serve to provide a more in-depth and informed view for maintaining manufacturing systems performance in the face of internal flux and external turbulence.

Finally, the purposeful development of governance functions can be instrumental in achieving enhanced unique capabilities beyond individual manufacturing systems. Poorly performing systems should be examined for deficiencies in either governance functions or their supporting communication channels. This level of system investigation can reveal a deeper understanding of the 'systemic' sources of deficiencies. In many cases, tracing deficiencies to underlying governance function issues and violations of system propositions might offer alternative paths forward for prioritizing and targeting system improvements. Therefore, a purposeful AMM system development must be supportive of a more rigorous, informed, and actionable approach to manufacturing systems. The challenge for AMM practitioners is to ensure that governance functions are being purposefully designed, executed, and developed to support current (and future) manufacturing system viability. For example, although the concept of viability is well documented, there has not been a significant movement to appreciate the insights that can accrue from the purposeful assessment of governance functions, their interrelationship, and the impact their holistic development might have for the acceleration and advancement of viable manufacturing systems.

The preceding six points are challenges associated with grounding AMM in the Systems Theory paradigm while attempting to project the paradigm to manufacturing systems viability. The present research offers an approach that can make several contributions to future efforts concerned with inculcating viability into the management of complex manufacturing systems to enable alternative levels of thinking, decision, action, and interpretation appropriate for the AMM problem domain.

Conflicts of interest

The authors declare no conflict of interest.

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