Expansionism-Based Design and System of Systems

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Facing the growing complexity within technological products and systems, traditional reductionism-based design approaches, which focus on decomposing and optimizing subsystems, components, and their interrelationships, will face greater difficulties in the search for future innovation. In such cases, expansionism-based design will be particularly effective because it reduces the need to deal with the superior internal complexity of existing systems and primarily explores design opportunities by integrating and synthesizing previously unrelated independent systems into a new system of systems. The system of systems that results from expansionism-based design may improve the functionalities and performances of the prior systems, or obtain novel functionalities of the system of systems from the synthesis. In this paper, we identify the system theory roots of design expansionism, and elaborate the value of expansionism-based design and how it enables design opportunities for systems-of-systems. We also preliminarily discuss potential concept generation methods to aid in expansionism-based design and the analytics of collective dynamics and emergent behaviors of the resulting system of systems in order to effectively architect and manage them.

I. INTRODUCTION

The technological products and systems that we design and use today are growing in complexity, with the inclusion of more and more components and parts and their increasingly intricate interdependences [1,2]. Facing such growing complexities, the traditional *reductionism-based design* approaches, which focus on decomposing and optimizing subsystems, components and their interrelationships within existing products or systems, may face greater difficulties in the search for future innovation. In the meantime, we have also witnessed the invention and surge of many systems of systems [3,4] in the past three decades, such as the Internet, intelligent transportation systems, smart grids, and the Internet of Things. Such systems of systems normally result from *expansionism-based design* approaches that synthesize existing and separately created systems, instead of decomposing them.

Expansionism-based design may reduce the need to deal with the internal complexity of existing systems, as it focuses more on identifying, integrating, and synthesizing previously existent but unrelated independent systems into a larger holistic system of systems. Therefore, when system designers face super complexities in components and system architectures that constrain their redesign potential via reductionism-based design approaches, expansionism-based design may enable additional out-of-the-box innovation opportunities. Expansionism-based design enables design opportunities for a system of systems that may improve the functionalities and performances of the prior systems, or create novel functions of the new holistic system of systems.

As we anticipate increasing complexities in future products and systems, the importance of expansionism-based design to enable systemic innovation is also expected to grow. This paper aims to formalize and systemize *expansionism-based design* and to provide preliminary guidance for system designers to pursue it. We will review the system theory roots of the reductionism-based versus expansionism-based design approaches, and discuss the advantages and benefits of expansionism-based approaches for the design of complex systems. We will also preliminarily discuss potential concept generation methods to aid in expansionism-based design and methods for the analytics on the collective dynamics and emergent behaviors of resulting systems of systems to support the architecting and management of them.

II. SYSTEM THEORY ROOTS OF DESIGN AND INNOVATION

2.1 Hierarchies, Decomposition, and Reductionism

In this paper, we take the classical definition of a "system" as a set of elements in which the behavior of each element has an effect on the behavior of the whole, and the behavior of the elements and their effects on the whole are interdependent [5-7]. The parts of a system will stop functioning and become useless if removed from the system. For example, an eye is a part of the human body but not a system by itself because it will stop functioning after the removal from the body system. Hierarchy is inherent in many types of complex systems [5,6], such as social, physical, and biological systems. Technological products and systems are also often understood, represented, designed, and managed as a nested hierarchy of recursive subsystems, components, and parts [8,9].

The design strategies and processes to search for the improvement opportunities of existing products and systems often comply with the hierarchical architectures of existing products and systems. Arthur [10] argued that new technical inventions emerge from an accumulation of previously created components and their functions. Funk [11] showed in detailed cases that many innovations in electronics resulted from the improvements in components and materials. Tushman and Murmann [12] suggested that the evolution trajectory of a technological system is conditioned by the designs and evolution trajectories of its subsystems and components and their coupling at lower levels in the system's nested design hierarchy. Searches for new technologies involve identifying the problem and a recursive process of solving the sub-problems and sub-sub problems. As a result, the hierarchical interdependences between components of a system influence the sequences of the related design processes [13] and the direction of related technological changes [14].

Based on the nested hierarchy view, Henderson and Clark [15] defined architectural innovation as a value-added change in the interrelationships between the system's components, without changing the existing components themselves. This contrasts with component innovations that do not change the relationships between components, but do change the components themselves. Baldwin and Clark [16] focused on system architectures that can enable autonomous and continuous modular innovations within the components. They showed how modular innovations drove technology changes in the personal computer industry. Stone and Wood [17] and Dahmus et al. [18] proposed actionable approaches to decompose a system's main functions into sub-functions and their interdependent relationships, i.e., the functional architecture of a product or system, and identify the modules that can be redesigned without requiring significant changes to other parts of the system.

2.2 Reductionism versus Expansionism

Given a problem to solve (e.g., improving fuel efficiency and safety) at the level of a complex system (e.g., an automobile), the system designer may implement two alternative design approaches differentiated by the orientations of the search along the system hierarchy: *reduction* versus *expansion*. The system designer may begin by decomposing a system such as an automobile into subsystems, i.e., engine, chassis, body, transmission, suspension, etc., and further into components and parts, none of which will continue to function if removed from the automobile. Then, the designer will seek a more efficient engine, streamline the car body, or change the system architecture (to hybrid-electric, for instance) and re-integrate the new parts with the rest of the system.

Alternatively, the system designer may begin by first conceptualizing a new and larger system (e.g., an intelligent transportation system) that contains the original system of design consideration (i.e., the automobile) and then consider redesigning the automobile in terms of its roles and functions to be played within the transportation system and redesigning the transportation system to improve the utility of the automobile. On that basis, the system designer may design better roads or infrastructures in the transportation system to allow automobiles to run more efficiently. The designer may also design new policies, such as CAFÉ (Corporate Average Fuel Economy), which are useful to coordinate the larger system of many automobiles that are stand-alone complex systems.

The first approach is based on *reductionism*, which decomposes the original problem into sub-problems to narrow down the focuses of the search for new solutions. Design is concerned only with the parts within an existing system and the interdependences among them. In contrast, the latter approach is empowered by *expansionism*, which expands the level of thinking and exploration beyond the original system boundary. It is similarly concerned with interrelationships, but the relationships are between the original design object, i.e., the focal system, and the other objects or systems in its environment. The *reductionism-based* and *expansionism-based* design approaches are expected to yield complementary rather than contradictory results.

There are considerable differences between these two alternative system design approaches. Reductionism-based design involves *analysis*, whereas the expansionism-based design involves *synthesis* [7]. Analysis looks into things; synthesis comes out of things. Analysis focuses on structure, as it reveals how things work. Synthesis focuses on function, as it reveals why things operate as they do. Analysis enables us to describe, whereas synthesis enables us to explain. Analysis yields knowledge, whereas synthesis yields understanding. Analysis is based upon reductionism; synthesis is based upon expansionism. Increases in understanding are believed to be obtainable by expanding the systems to be understood and not by reducing them to their elements.

In the design and innovation literature and practices, *reductionism* has been the most popular logic for describing technological innovations, as well as the logic behind many traditional design methods that have been used to pursue technological innovations (see a review in section 2.1). In contrast, *expansionism* has been largely overlooked, and it can create additional design possibilities for complex systems. Therefore, when something does not work satisfactorily from within, i.e., reductionism, one can think beyond the original system boundary and work out new solutions from the outside, i.e., expansionism.

III. EXPANSIONISM-BASED DESIGN

3.1 Definition and Examples

Expansionism-based design encapsulates the focal system by connecting and synthesizing it with other systems, which were previously unrelated, to solve a problem of the original system, improve it, or generate totally novel and useful functions from the new and greater system of systems. Fig. 1 illustrates such an expansion of the boundary of thinking and design. The product or service that used to be treated and analyzed as an independent system now becomes a “component” of a larger system of systems. Such component systems could maintain a high degree of autonomy while also contributing to other systems. Expansionism-based design extends outward from the existing system design hierarchy so that it becomes a sub-hierarchy of a new and larger hierarchy of the system of systems. It contrasts with reductionism-based design, which focuses on the inward analysis of existing design hierarchy. The expansion makes the analysis of internal complexity less necessary and enables additional out-of-the-box design opportunities.

Some examples of expansionism-based design are presented in Table 1, including a market (the expanded system) compared with an individual person, (the original personal computers (the original system), and *Better Place*’s network of battery swapping stations (the expanded system) for electrical vehicles (the original system), among others. The table lists the original systems that were to be synthesized, their components, the system of systems they form, and the types of linkages that connect them.

Note that both system architecture design [15-18] and expansionism-based design are recursive and are about the design or redesign of “interrelationships”. Their differences lie in the differences between *analysis* and *synthesis.* System architecture design arises from redesigning the relationships between non-decomposable or nearly decomposable components that cannot function autonomously or independently if removed from the system. For example, an airfoil does not fly if separated from an airplane. In contrast, expansionism-based design creates new interrelationships for systems to interact with the others that were previously unrelated. A larger system of systems that contains and synthesizes the original systems must be conceptualized, defined, and created. If the new connections among original systems are removed, the original systems could still function independently, just without the value-added from the synthesis of a system of systems.

This difference can be demonstrated using two contrasting examples: the Internet and a telephone network (see Fig. 2). The Internet that connects computers was created via *expansionism-based design* because computers were invented prior to the Internet and had their own independent functionalities. A computer itself was made not of autonomous systems but rather of recursive subsystems and components that provided no value individually. Thus, a computer itself is a system, and the Internet is a system of systems. By contrast, the telephone and telephone network were invented simultaneously as non-separable components of a functional system. A telephone by itself has no value if it is not connected in a network with other telephones. A telephone is a part rather than a system, and the telephone network is a system. Therefore, the invention of the telephone network was not an *expansion* or *synthesis* of telephones. Since its invention, the telephone network as a system (not a system of systems) has experienced many component innovations in the telephones and architecture innovations in the infrastructure that connects the telephones. In brief, the telephone network was invented as a system, and many improvements to the phones were achieved via component innovation, whereas the Internet was invented as a system of systems via expansionism-based design.

Another example of such a comparison could be a power plant versus a co-generation plant. A coal power plant solely generating electricity and a boiler solely generating heat are *synthesized* together in a co-generation plant to simultaneously provide both electricity and heat (from the

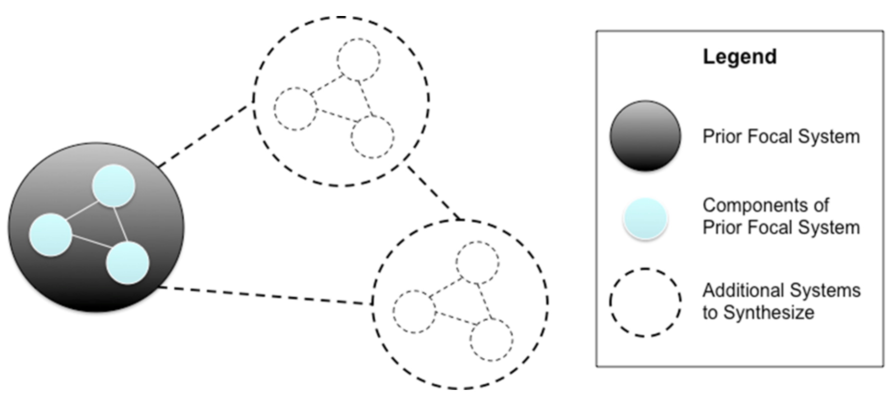

FIG. 1. Expansionism-based design to synthesize the prior focal system with other previously unrelated systems.

TABLE I. Examples of expansionism-based design.

	Original "Systems" that Later Become Components of a System of Systems (independently functional)	**Components of Original Systems** (no longer functional if removed from system)	**System of Systems** (synthesis of original systems)	**New Linkages** (information, energy, material, energy)
1	Human	Productive behaviors	Market	Information
2	Power plants	Boiler, steam turbine	Emission trading system	Information
3	Personal computers	Chips, disk drive, etc.	Internet	Information
4	Personal websites	Advertisements on page	Google AdWords	Information
5	Electrical vehicles	Battery, motor, etc.	Network of battery swapping stations	Materials
6	Thermal power plant, and heat boiler	Boiler, turbine, etc.	Co-generation plant	Materials and energy
7	Cell phone, computer, camera	Chipset, board, keyboard, led, etc.	Smartphone/handset, which synthesizes the functions of phone, computer, internet, camera, etc.	Materials, information, energy
8	Cars and the OnStar system	Car components, OnStar equipment, etc.	Vehicle telematics service, including in-vehicle security, turn-by-turn navigation, and remote diagnostics	Information

hot steam exhaust after the turbine process) so that the total efficiency of producing either product is improved through the expansion of design boundaries and synthesis. A co-generation plant is a system of systems, whereas either a coal power plant or a boiler is an independent functional system. The invention of the co-generation plant was expansionism-based. In contrast, reductionism-based design efforts may seek a better chamber structure to improve a boiler or a better steam turbine to improve a power plant.

3.2 Advantages of Expansionism-Based Design

When designing complex products and systems with many interdependent components and intricate interdependences among them, *expansionism-based design* may be more desirable and powerful than *reductionism-based design*. Architectural and modular design efforts search inward through the design hierarchy of a technical system, and therefore, they do not depart from the original concept but rather only reinforce existing functions and mechanisms. Reductionism-based design represents exploitation and is conservative by nature. When the original system or design problem is highly complex and coupled, such approaches may be ineffective in identifying creative solutions because redesigning one component would require the redesign of many other interdependent components due to their intricate coupling.

In such cases, expansionism-based design may be more desirable because it does not require solving the insurmountable challenges that lie within the existing complex system, but aims to discover design opportunities outside the current box of complexities. Expansionism-based design searches outward or upward from the existing design hierarchy of an existing system for design opportunities to link and engage previously unrelated systems. It is therefore more exploratory by nature. To solve rather complex design problems, it will be more advantageous to yield novel out-of-box solutions than reductionism-based design.

For example, the technological evolution of cars has been primarily driven by architectural and modular innovations inside the system of a car, i.e., reductionism-based design. Over time, continual refinements in subsystems,

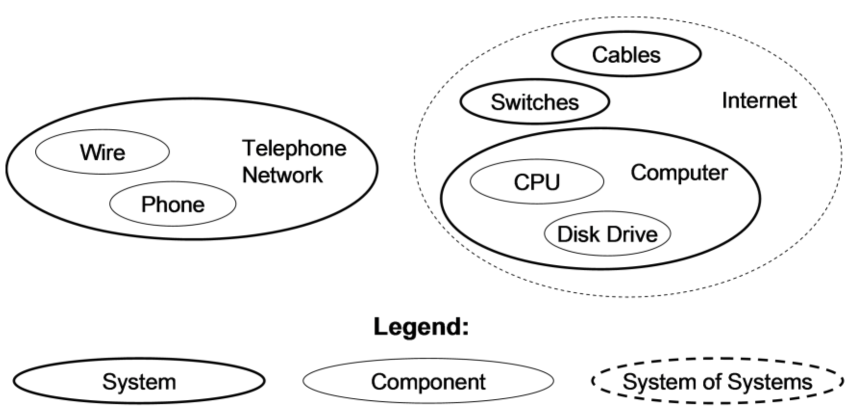

FIG. 2. System architectures of the telephone network and Internet when they were invented.

components and their architectures have indeed reinforced the existing dominant design of contemporary cars, and increased the physical and information coupling of the components and parts of a car. The increasing complexity, i.e., interdependences and interlocking relationships between thousands of components and parts within a car, makes it increasingly difficult for either architectural or modular innovations (inside the system) to be achieved. Therefore, expansionism-based design, via searching outside of the existing car design hierarchy and conceptualizing a potential larger system of systems that synthesizes individual cars, may be more likely to create breakthrough designs and innovation opportunities.

For instance, for many decades, electrical vehicles (EVs) have been expected to replace the dominant internal combustion engine (ICE)-powered vehicles. However, the required battery recharging time of 7~8 hours and the limited energy and power densities of battery technologies have long hindered the usability and thus mass adoption of EVs. Battery technologies have undergone only limited improvements in the past century and are still insufficient to allow EVs to compete with traditional cars in actual use. Facing the battery bottleneck within an EV, *Better Place*, a venture-backed company founded in 2007, invented a *system of systems* solution that aims to improve the usability of individual EVs without requiring a leap in battery technologies. The solution looks beyond a single car and allows EV drivers to swap exhausted batteries with fully charged ones in 3 minutes at battery swapping stations, instead of taking 7~8 hours to charge the batteries fixed in cars. *Better Place* also planned to integrate the large battery stocks that they hold at swapping stations into intelligent electricity grids; therefore, they can charge the batteries when market electricity price is low and sell excess electricity from its battery stocks to the grid at peak hours. Via optimizing electricity trading, their electricity is expected to be cheaper than that in households, providing an economic incentive for EV owners to drive to *Better Place* battery stations to swap batteries, instead of charging their EVs at home.

Fig. 3 illustrates *Better Place*'s design of a system of systems. The electrical vehicles, the battery swapping stations, and the electricity grid are stand-alone systems that can function independently. The synthesis of them was aimed at reconciling the economic and technological constraints on electrical vehicle usability. The battery swapping station in particular connects electrical vehicles and the electricity grid, and this connection benefits both of them. Designers and operators of the electricity grid might view the swapping station as a large electricity storage (sub) system to provide a buffer for the grid, even if not thinking of the electrical vehicles.

This particular system-of-systems invention exemplifies *expansionism-based design*, as it expands the design boundary from that of an EV to a larger system of systems that synthesizes EVs, battery swapping stations, battery stocks and electricity grids, to solve the insurmountable economic and technological challenges faced by individual EVs, i.e., the original system. The larger system of systems synthesizes individual electric cars by sharing and swapping their batteries. Therefore, each individual electrical car user can benefit from the shortened charging time from 8 hours to several minutes. The prices they pay for electricity would also potentially be lowered because of the financial optimization through the trading of electricity between the electricity grids and the large quantity of batteries held at the network of swapping stations.

This example implies that expansionism-based design can be especially useful and is more likely to yield novel solutions for complex systems such as cars, trains, and airplanes, where modular and architectural innovations have become extremely difficult to achieve due to the prominence of a highly complex and coupled dominant system architecture.

IV. SYSTEMIC IMPLICATIONS

4.1 Expansive search methods

The foregoing section has shown that expansionism-based design offers value for innovation in complex system design. To pursue expansionism-based design, expansive thinking habits and exploratory mindsets of system designers are necessary. More structured methods are also needed to guide systematic exploring and conceiving of new systems of systems, encapsulating the previous system that the designer used to focus on. Several recently developed engineering design methods have the potential to

FIG. 3. *Better Place*'s expansionism-based design of a system of systems.

aid in an expansive search for novel concepts of systems of systems. For instance, the infused design [19] framework may empower system engineers to discover new types of relevance between other technologies/systems and the current focal system from a multidisciplinary perspective. The patent search method based on functional analogy [20] may allow system designers to identify and bring new technological systems in other fields of different "distances" from the focal one for potential synthesis together into a new system of systems.

4.2 Coordination, interfaces and standards across systems

Despite its usefulness, expansionism-based design also faces new and unique challenges in practice. The first is the coordination among prior systems, which were separately designed prior to the synthesis. Therefore, protocols and standards are essential to enable interoperable systems and their effective synthesis [4,21]. However, setting protocols and standards can be difficult when the designers, operators, and other stakeholders of the component systems have heterogeneous interests and incentives [3,4]. In the example of *Better Place*, to achieve sufficient economy of scale, the batteries stored and swapped at *Better Place*'s stations need to share technical standards with those of the electrical vehicles designed and made by different automobile manufacturers, e.g., Tesla, Toyota, and General Motors.

However, the EV manufacturers would be naturally concerned that *Better Place* will dominate the system of systems, marginalize them, and capture most of the value created, if it sets the technical standards. In fact, *Better Place* successfully convinced and collaborated with Nissan to share battery standards. *Better Place* went bankrupt in 2013 due to financial and operational challenges. Interestingly, around the same time of the bankruptcy of *Better Place*, Tesla Motors started to offer a 90-second battery-swapping option, similar to that of *Better Place*, in its supercharging network. Compared with *Better Place*, Tesla Motors has advantages in realizing the system of systems because it designs and produces its own electrical vehicles, batteries, and battery swapping systems in house. Coordination and standard setting is relatively easier.

This case illuminates alternative approaches to address the challenges to setting and implementing interface standards across agents. For instance, one approach is to form alliances, such as the one between *Better Place* and Nissan, and industry consortiums or associations, such as the *Internet Engineering Task Force* that develops and manages technical standards of Internet technologies, to facilitate coordination and collaboration. Alternatively, the designer that used to focus on a component system may further expand its design, operational and business scopes to cover other component systems as well as the interfaces among them, such as Tesla expanding its scope from EVs to the supporting infrastructures.

4.3 Prediction of emergent behaviors

Because the component systems of a system of systems are autonomous by nature, to some degree, after the synthesis, there might be *collective* and *emergent* behaviors from the interactions of such semi-autonomous systems and their designers and operators [3,4]. One example is the rapid diffusion of a computer virus across Internet. Therefore, the success of expansionism-based design also requires the development of the capabilities to predict, assess, and manage potential emergent behaviors of the resulting system of systems. Recent studies have suggested agent-based models to represent a system of systems and analyze the interaction dynamics among agents [22]. Graph theory and complex network analysis may also be used to predict the propagation of information or design changes across autonomous systems and aid in the design of the architecture of the new system of systems [23]. More research and development is still needed to allow such general models and analyses to generate practical insights on the design and management of systems of systems.

4.4 Impact on innovation and competition landscapes

Expansionism-based design may also affect innovation and competition dynamics in related markets and industries, in both undesirable and desirable ways. For instance, successful expansionism-based design stimulates modular and architectural innovations inside the original systems, while the synthesis demands changes in the functional goals, design mechanisms, and parameters of these now component systems. For example, the diffusion of smart phones and mobile internet has resulted in demand for smaller and more powerful processors, smaller and faster communication chips, more efficient memories, larger handset screens, and more advanced operating systems, which are most likely to be improved via component and architectural innovations. Clearly, engineers and firms specialized in such component niches will also benefit from the pull from the emergence of a new system of systems.

New systems of systems may also increase the market demands for the original systems that are now synthesized. For example, if the battery-swapping infrastructure prevails, the use feasibility of electric cars will be improved, and the demand for electric cars will be stimulated. However, in other cases, the growth of the new system of systems may limit or replace the needs for the prior systems that it now encapsulates, thus threating the designers and firms specialized in them. For example, smart phones have increasingly encroached upon the market shares of basic mobile phones as well as digital cameras. Consumers are less interested in buying standalone basic cell phones and cameras, as they can use the corresponding functions that have been synthesized into their smart phones. The firms that were specialized in designing such prior systems need to adapt and make their system designs compatible with the system of systems, and be able to harvest the value created from the synthesis with others.

Therefore, when pursuing expansionism-based design, it is necessary and important for the designers and companies to evaluate the potential social-technological and competitive impacts of the anticipated system of systems and to prepare themselves with relevant capabilities potentially required to address those changes. Many of these issues transcend the basic assumptions in traditional engineering design and require new ways of thinking and new system design and management methods, drawn more upon system sciences, complexity studies, and evolutionary theories. Well-prepared system designers and firms may better capture the value created by expansionism-based design and the resulting system of systems and minimize the associated risks of undesirable resultant changes in technologies and markets.

V. CLOSING REMARKS

The purpose of this paper is to advocate expansionism-based design, which has been largely ignored or not been explicitly used in design and innovation literature and practices, compared with reductionism-based design. Expansionism-based design complements reductionism-based design and can enable additional innovation opportunities by synthesizing existing systems and creating systems of systems. We argue that it is most advantageous and powerful for designing and managing highly complex systems, for which opportunities for component and architecture innovations are limited by the intricate interdependence architecture and component performances. Therefore, as we expect the complexity in contemporary technologies and systems to monotonically rise in the future [1], the importance of expansionism-based design for system innovation is also expected to increase.

To aid in expansionism-based design, some recently developed engineering concept generation methods can be leveraged, for example, infused design and design-by-analogy patent search methodology. In the meantime, expansionism-based design and its resulting systems of systems may require cross-agent coordination and setting standards and protocols for the interfaces of the component systems. To reconcile potential conflicts of interests and synchronize incentives of agents designing different component systems, alliances and consortiums may be beneficial for the participants. Alternatively, to avoid the agent problem, the designer of certain component systems may expand its scope to integrate the design of other component systems and the interfaces among them. In addition, the resulting systems of systems may have unpredictable, either desirable or undesirable, impacts to the existing technological and competition landscapes. Agent-based modeling and complex network analysis are potentially useful for system designers to predict the collective dynamics of the potential system of systems for evaluation and aid in system architecting.

In general, to harvest the benefits from expansionism-based design and the resulting system of systems, system designers and their companies need to develop relevant capabilities and approaches for the boundary-expanding search for new system of systems concepts, for predicting and managing emergent behaviors and collective dynamics of the system of systems, and for architecting the system of systems. We hope this paper can be seen as an invitation for more academic research into the development of theories and methods to aid in expansionism-based design and the analysis, architecting, and management of the resulting system of systems.

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