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Lean Systems Engineering: Research Initiatives in Support of a New Paradigm

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Abstract

Systems Engineering (SE) has become increasingly important as the complexity and interconnectedness of systems continues to grow, but there remains a great deal of uncertainty as to how and when systems engineering can most effectively and efficiently add value throughout a program's lifecycle. Lean Thinking (Lean) is the dynamic, knowledge driven and customer-focused process through which all people in a defined enterprise work continuously to eliminate waste and to create value. SE and Lean have overlaps and differences, but both represent processes that evolved over time with the common goal of delivering product or system lifecycle value to the customer. SE has emphasized technical performance and risk management of large, integrated complex systems. Lean has emphasized waste minimization and flexibility in the production of high quality affordable products with short development and production lead times. With SE and Lean sharing a common goal, some suitable combination of the two could possibly lead to a superior systems engineering process, herein called *Lean Systems Engineering*. This paper will highlight recently completed and ongoing research activities at the Lean Aerospace Initiative (LAI) Consortium research center at MIT that point towards an emerging lean systems engineering paradigm, and will offer thoughts on additional possibilities for research directions, including extensions to Systems of Systems.

1.0 Introduction

This paper reports a promising new paradigm for Systems Engineering (SE), which we term Lean Systems Engineering. It is based on the cumulative experience of numerous research projects and years of collaboration in the Lean Aerospace Initiative (LAI) consortium. The LAI Consortium is a unique organizational entity that brings together senior level program leadership from government and industry, experienced practitioners, labor, and leading university researchers. The consortium shares a common belief that lean principles and practices (hereafter Lean) provide an effective approach to elimination of waste with the goal of creating value, and are particularly powerful when an enterprise or system level perspective is taken. LAI researchers at the Massachusetts Institute of Technology help focus understanding and application of lean, enterprise, and value principles by building on nearly a decade of knowledge generation, consolidation and deployment in industry and government. The evolution of LAI research, particularly that focused on product development, SE, or related topics, has shown a compelling case that Lean and SE are not only compatible, but potentially powerful allies in the development and realization of complex systems.

2.0 Lean Systems Engineering

Neither practitioners nor researchers are likely to associate SE and Lean with one another at first glance. SE emerged predominately from the U.S military and civil space program in response to the need for technically demanding systems to work flawlessly upon initial deployment[1]. With this heritage, SE has emphasized technical performance and risk management of large, integrated complex systems. Activities and practices typical of SE are shown in Table 1.

Table 1. Typical SE Activities.

SE Activities	Examples
SE Technical Management	SEMP, IPPD, scheduling, risk management, SE process metrics, TPMs, reviews and audits
System Design	Requirements definition and solution definition processes
Product Realization	Baseline maintenance, requirements and design loops, prototyping, system integration, V&V
Technical Analysis and Evaluation	Analyses Including: deployment, design, environmental impact, human systems engineering, LCC, manufacturing and producibility, mission operations, reliability/maintainability/availability, safety and health hazard, supportability and integrated logistics support, survivability, system cost/effectiveness, system modeling, system security, trade studies, training, verification, and disposal
SE Product Control	configuration and data management
SE Process Control	standard SE processes and practices, reviews, audits, lessons learned, analysis and change definition
System Post-Implementation Support	SE support to manufacturing, sustaining engineering

Adapted from:.(1)

The practices in Table 1 indicate that SE processes primarily ensure that "nothing falls through the cracks" in terms of technical performance, internal and external interfaces, cost and schedule, operational needs, regulatory and other requirements. Experience has shown that ignoring any of these can lead to difficulties. It is evident that SE embodies rigorous methods to assure that a system or product is developed to perform as expected by the customer. While these SE activities address the entire lifecycle of a product, closer inspection shows that many of the activities are invoked in the earlier stages of a product lifecycle, principally from concept exploration through detailed design. Therefore, while it is the most encompassing of engineering disciplines, SE still retains a strong engineering core identity.

Lean emerged from the Japanese automobile industry in response to the need to deliver quality products with a minimum use of resources[2]. Lean has emphasized waste minimization and flexibility in the production of high quality affordable products with short development and production lead times. In the United States, Lean has typically been associated with manufacturing in general and with the Toyota Production System (TPS) specifically. Womack and Jones[3] helped in the implementation of that system with their five steps to implement Lean Thinking, shown in Table 2 below.

Table 2. Five Steps of Lean Thinking

Step	Description
Specify Value	Value is defined by the end customer
Identify the Value Stream:	The set of all specific end-to-end and linked actions, processes and functions necessary to transform information or raw materials into the product expected by the customer, and then provide post-delivery customer support. Actions either a.) create value; b.) create no value but are necessary or unavoidable; c.) creates no value and can be eliminated. Action focuses in minimizing non-value added activities.
Make Value Flow Continuously:	With non-value added activities eliminated, next all bottlenecks to the smooth flow of information or material processing (indicated by work-in-process—WIP) are removed. Lean relentlessly pursues the elimination of such WIP.
Let Customers Pull Value:	Deliver the value when it is expected by the customer ("just-in-time"), and use this to "pull" value from all "upstream" activities.
Pursue Perfection:	Lean is not a "state", but a "journey" in which continual improvement is sought to make processes better and better—as measured by their value delivery.

Adapted from (3)

As Lean has been embraced more widely, it has expanded beyond its roots in the production environment to accommodate expanded and more challenging contexts. Murman, et al describe *Lean Thinking* as the dynamic, knowledge driven and customer-focused process through which all people in a defined enterprise continuously work to eliminate waste and to create value[4].

There are key differences and similarities between SE and Lean that are worth noting. First, both SE and Lean emerged from practice; their respective precepts, principles, and theories were codified later. SE and Lean have traditionally focused on somewhat different phases of the product lifecycle with their respective challenges and realities. The traditional domain of SE practice is generally product development, while the traditional domain of Lean practice is generally production. SE is traditionally focused on those activities that lead to the definition (from requirements to detailed specifications) of the product that is most likely to successfully meet customer needs. On the other hand, Lean is traditionally focused on those activities that lead to the realization of the product that will successfully provide the customer with value.

With this difference in areas of focus of lifecycle phases, SE has more of an emphasis on planning, while Lean has more of an emphasis on empirically-driven action. Within the SE context, value might be represented by a measure of risk (that is, as risk decreases, value created increases)[5]. SE process activities have been honed to reduce the risk (performance, cost and schedule) of large, complex, highly-integrated systems as the means to create value. In order to accommodate the intricacies of producing a complex system that performs as required to provide the customer with value, SE strives to create the perfect plan or architecture that has minimal risk in execution (with attendant processes, tools, structures, artifacts, etc.)

On the other hand, in order to accommodate continuous improvement in a complex production environment, Lean strives to enable all stakeholders to understand, assess, and improve their respective processes, with the expectation that the entire enterprise will evolve its way towards perfection. People are central to successful Lean implementation. Lean emphasizes tools and practices that can take advantage of the knowledge and skills of all participants in the system to reduce waste, poor quality, delays, or unnecessary investment. In the production context, customer value relates directly to product cost, quality, and timeliness.

In contrast to Lean, there is relatively less emphasis in SE on quality principles, empowerment and capability of people executing process activities, smooth flow of information to eliminate bottlenecks, continuous improvement, or maximizing the value added by each process activity. Integrated Product and Process Development (IPPD) and Integrated Product Development Teams, or IPTs, are notable exceptions. It is clear that IPPD and IPTs have brought an important multifunctional human and communication element to SE with beneficial outcomes. IPPD and IPTs are also central elements of Lean.

Despite the important differences between SE and Lean, we believe that that two ultimately strive for the same objective, and therefore are compatible and even critically linked. The domains of Systems Engineering (SE) and Lean Thinking (Lean) both represent processes that evolved over time with the common goal of delivering product or system lifecycle value to stakeholders. Generally, one can consider lifecycle value as some combination of product performance, quality, cost, and availability as defined by customer's needs[4]. Because of their different legacies, Lean and SE have emphasized different elements of this common goal. But, if the objective of a complex system is indeed to provide some optimal or best lifecycle value to a customer or user, then both SE and Lean have important roles to play. The following section discusses research that illustrates how both SE and Lean can play a role in creating value in complex systems.

3.0 Research Findings Linking Lean and Systems Engineering

Research at the LAI began some 10 years ago focused on the traditional domain of Lean—the production process—applied in the context of complex aerospace systems. There was strong and positive evidence that Lean applied in this setting was able to produce significant improvements in process outcomes. For instance, the hours required to assemble floor beams on large commercial aircraft were reduced by roughly 50% and fixed tooling was virtually eliminated through the use of Lean practices6. Research in areas outside of traditional production environments such as software process automation showed similar levels of improvement when lean principles were applied[7].

A challenge for LAI consortium members and researchers came from the observation (often from a customer vantage) that despite significant evidence of success in process improvement, the overall (i.e., "flyaway") cost or quality of many complex aerospace systems was not changing significantly. There are a variety of reasons to explain this outcome, including the nascent and uneven implementation of Lean in the aerospace context in the early years of the LAI consortium. Some notable early exceptions were the C-17 and JDAM programs. Nevertheless, it became clear to many researchers and practitioners alike that in a complex organizational system that designs, produces, and procures complex product systems, there is an important role for both grass-roots improvement and evolutionary change towards perfection as well as systemic and architectural improvements at the level of the entire system or enterprise. More about this evolution in perspective is captured in Murman, et al[4].

The scope of research at LAI has evolved to include many of the enterprise processes that span the product lifecycle, including many of the SE processes that are found in Table 1. Figure 1 illustrates the scope of recent LAI research over the product lifecycle. It is based on a sample of 36 recent LAI research projects (primarily graduate thesis research) selected from well over 100 LAI studies based upon their applicability to the SE lifecycle stages. The height of the bars indicates the number of research projects that had noteworthy findings or implications for that phase of the product lifecycle (the vast majority of research projects had such implications for more than one phase of the product lifecycle.)

Figure 1. Recent LAI Research Findings Across the Product Lifecycle.

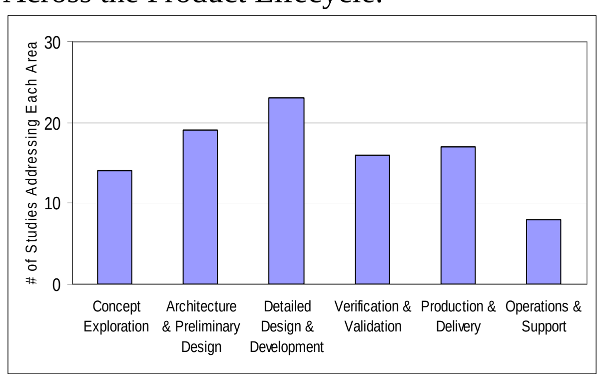


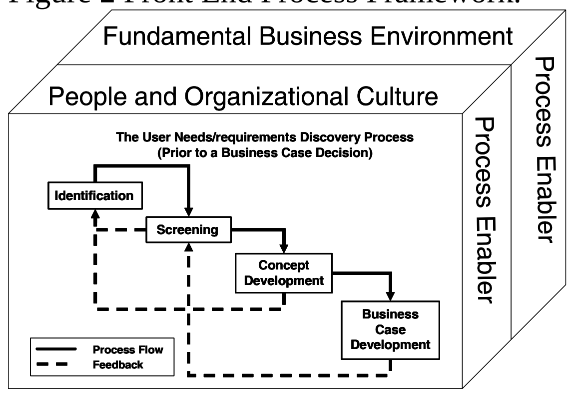
Figure 1 provides a rough indicator of how research focused on Lean has in fact addressed a broad spectrum of complex system realization activities. These research projects were related to Lean because they focused on improving the creation of value for the customer and other enterprise stakeholders. Many included value stream thinking or tools as part of the framing of the research and/or the empirical investigation. They are linked to SE in that the processes studied, and analyzed for improvement included the lifecycle processes that are part of the realization of complex products, including many directly associated with SE. This Lean research falls squarely in the domain of SE practice and found evidence that these practices can be improved through the application of Lean. Perhaps more importantly, they are beginning to show cumulatively that higher levels of performance in the realization of complex systems may require a combination of both Lean and SE perspectives and practices. It is impossible to convey in the space available here that cumulative weight of evidence. However, a few research projects have been selected to illustrate how Lean and SE have coexisted and mutually benefited the research process.

3.1 The Front End of Product Development

This study examined the processes that make up the so-called "fuzzy front end" of product development and lead to the decision to launch a program[8]. The motivation for the study was prior research findings that a significant source of cost growth in government and commercial aerospace system development programs came from program instability[9]. Not only was a significant program cost growth found due to requirements problems, but also a strong link between budget instability and poorly performing front end process.

A framework shown in Figure 2 for assessing process maturity was developed based on an extensive review of past product development research in the literature, and formed the basis of a benchmarking survey used to collect process characteristics data. The front end process value streams from idea generation to program launch were mapped for 17 organizations, including 9 military organizations and 8 commercial organizations. Additionally, several other military organizations provided background information.

Figure 2 Front End Process Framework.



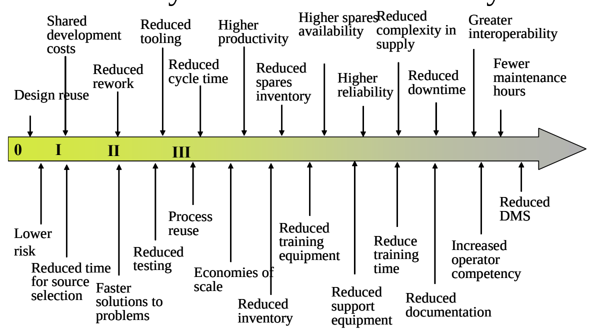
Examples of practices that distinguished the higher-performing organizations from lower-performing ones included the use of multiple, structured methods to identify requirements for the concepts; use of prototypes and models to generate data for tradeoff analyses; and prioritizing product features and establishing exit criteria prior to the launch decision. Importantly, the higher-performing organizations also had organizational and cultural enablers that made a difference, including the use of dedicated, stable multidisciplinary teams for analysis and concept development, engagement of senior leadership throughout the process and in decision gates, and information systems that allowed decisions to be made based on strategic and other well-defined organizational criteria. The reward for such structured processes was much fewer, but more manageable (from an organizational resource and capability standpoint) program starts than those organizations with lower-performing front end processes.

Those familiar with high-performing front-end decision processes and particularly stage-gate processes may not be too surprised by the findings of this study. What is noteworthy here is that several themes and processes from SE and Lean were commingled in this study. The motivation for this study was classically Lean: to enable higher program performance by reducing instability in key inputs (requirements and funding) and to improve the flow of work (program requirements) through the product development cycle. Value stream mapping played an important role in collecting the data to characterize these organizations' processes. However, this research is squarely in the domain of SE, and many of the processes studied are SE processes. The key insight gained by including Lean and SE in this one study is the importance of organizational and management processes to successful outcomes in the front end requirements process.

3.2 Design Implications for Multiple Complex Systems

This research explored the benefits of standardization and commonality across multiple complex aerospace systems[10]. It was motivated in part by prior research that had shown that high-performing Lean automakers in Japan had successfully used commonality as a way to reduce cost and cycle time[11]. This research added to the prior findings by studying complex aerospace systems, as well as extending the scope of the study beyond the OEM producer value stream to also include the user/operator. Twenty one (21) programs were studied, resulting in 8 case studies based on data from interviews with 84 respondents. Finding comparable data, especially across such a large value stream, was difficult as organizations often don't consider, let alone measure the effects of commonality. A composite perspective of the value stream from development and production through operations and support was created from the disparate data. This research identified the impacts of subsystem commonality over the lifecycle of a complex system, which are shown in Figure 3.

Figure 3. The Impact of Subsystem Commonality Over the Product Lifecycle.



What this study concluded was that commonality made the most sense at the subsystem level. Examples include motors, hydraulic equipment, antennas, navigation equipment, electronic warfare (EW) equipment, displays, optical equipment, communications equipment, transponders, etc. It makes sense at this level because requirements across multiple platforms are easier to reconcile, common subsystems will impact the logistics footprint and repair activities of weapon systems that deploy together, and subsystems are sufficiently high cost to make it worth the additional challenges. Commonality was not felt to be advantageous at the system level because of the difficulty of reconciling different mission requirements. Overall, the use of subsystem commonality was estimated to lower subsystem acquisition costs by 15-40%, and to lower annual operations and support costs by 20-45%, based on the cost structure of the specific system. Importantly, it can also concentrate knowledge and expertise in the organizations that specialize to develop, produce, acquire, and support these subsystems, so that they can be more rapid at implementing improvements or new technical innovations into a subsystem family.

A key insight from this research is that from a customer value perspective, individual aerospace systems often operate, deploy, and sustain in "packages" comprising multiple platforms and organizations. However, since there is typically no single "owner" for these packages of systems, it is difficult to make the kinds of binding decisions across multiple platforms that are needed to adopt a commonality strategy. Moreover, incentives for the development of individual systems often focus on maximizing the programmatic performance of that system only, so accommodating the needs of other systems is unattractive. In the case of this research, it is apparent that a traditional approach to developing a system architecture may not result in the creation of the most value and capability for the customer. The lifecycle value perspective from Lean and the use of the value stream across multiple systems and organizations provided important perspective into how to make choices about system architecture in complex aerospace systems. It provides another example of Lean and SE both benefiting from a perspective combining them together in research.

3.3 Software Development Value Stream

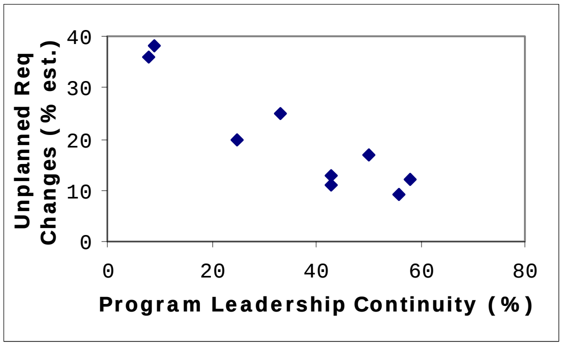
This research involved a comprehensive look at government and industry practices for deriving software requirements from system requirements[12]. The motivation for the study came from LAI consortium members eager to experience process improvement in the area of software development similar to that seen in other areas of lean implementation. The LAI Lean Enterprise Model (LEM) was used as a guide for the investigation. The LEM is a compendium of LAI research findings, organized in a hierarchical framework of 12 overarching lean practices supported by underlying enabling practices[13]. In addition to the LEM framework, a value stream view was adopted. Ten (10) mission critical software upgrade programs were studied in four application domains: military avionics, military space ground terminal, commercial aircraft, and missiles/munitions. Additionally, 3 detailed case studies on military avionics, commercial auto-pilot, and space ground terminal programs, respectively, were completed.

Among the major findings, the study found that there were few enterprise-level metrics for the end-to-end software development process in place. Even though the objective of these programs was to provide an operational capability to a larger system, the processes and stakeholders used to complete that task were remarkably fragmented. For instance, the responsibilities for assuring that software requirements "meet the end users needs" and "are cost effective" was found to be divided among multiple process owners. Not surprisingly, when measures were taken to provide continuity of effort, performance improved. There was a positive correlation between reduction in unplanned requirements changes and leadership involvement in both concept definition and requirements analysis phases as shown in Figure 4

Perhaps the most startling aspect of the study was the perspective given by the value stream research lens. In terms of overall cost to deliver the software capability for the military avionics case study, roughly half was not attributable to software proper (it involved ancillary items such as sensors, trainers, documentation, etc.). The other half of the design and development cost was related to software.

By looking at the entire software development value stream, this study found that code generation accounted for only about 6% of the total cost of the delivered product. Much greater costs were associated with validation and verification.

Figure 4 – Impact of Leadership Continuity on Concept Definition and Requirements Analysis for 9 Software Upgrade Programs.



This study again emphasizes where both Lean and SE may play important roles in creating value for the customer. Many of the requirements practices and management strategies seen as important to improving performance in this study would likely be regarded by some as "good systems engineering"—underscoring the importance of SE in performance improvement. Implementing good SE practices without the customer value stream perspective might lead one to make investment in processes (e.g., improving the efficiency of coding) that had minimal effect in the flow of value through the system.

4.0 Lean SE Research Enablers

Future research exploring Lean SE, based on the work cited here, will benefit by working from the respective strengths of each knowledge domain. From Lean, that includes a stakeholder value perspective that reaches from the earliest definitions of the product through its use in operation. From SE that includes specific domain knowledge of the tools and processes used to architect systems, manage risk, and identify and analyze the tradeoffs involved in the realization of complex systems. Gaining the broad scope of perspectives needed for such research can be a challenging task for individual researchers and groups.

Fortunately for the emerging Lean SE paradigm, the LAI consortium provided a venue that brought together stakeholders and researchers from a variety of backgrounds and product lifecycle perspectives to form a learning community at the national level. The length of this paper does not permit a detailed explanation of how such a consortium can function effectively. But our experience indicates that this has been a critical element of undertaking meaningful research on a topic as broad as Lean SE. (see the preface of Murman, et. al[4] for further details)

There are also networking opportunities for developing and sharing a Lean SE perspective within, but not exclusive to LAI. Within LAI, there is the LAI Educational Network that includes universities interested in sharing knowledge about Lean and related topics. A subset of the LAI Educational Network is devoted to exploring Lean SE. Outside of LAI, professional and academic societies have traditionally provided a venue for pooling expertise and perspective on challenging issues. These societies may also enable the advance of the Lean SE paradigm, perhaps through focused interest groups.

5.0 Areas for Future Research.

Lean SE is an emerging field. As such, there is much to learn, even with respect to establishing appropriate boundaries of inquiry for the field. However, in contemplating the fusion of two established knowledge areas, one can imagine at least three general strategies for developing new research streams, based simply on permutations of the existing areas.

The first stream of potential research would involve exploring how traditional SE practices could become more "lean". Womack and Jones' Five Steps to Lean Thinking have been widely applied to many processes beyond manufacturing, including product development and engineering, transactional processing, and analysis of enterprise level activities. It would seem logical to apply them to systems engineering. SE guidelines indicate that SE should be tailored or applied uniquely to each project. The value principles of Lean could provide a well developed and structured framework for this, for example, the use of Value Stream Mapping. Applications of Lean to SE could directly build upon existing risk management methods of SE. Some research efforts at MIT [c.f., 5, 14] have aimed at developing quantitative tools for modeling risk management and risk reduction in product development. Often people ask "how much systems engineering is needed" for a particular project. The goal of Lean Systems Engineering would be to answer this question with a structured approach which delivers the best value to the end customer in terms of system performance, cost and schedule—all with a focus on acceptable risk.

The second potential stream of research would be to make Lean more systems-oriented. SE provides a structured method for managing the requirements, system elements, interfaces, validation, and operational analysis of complex systems. Traditional Lean has often been applied in an opportunistic fashion. Is there some benefit to using the structured methods of SE to provide a more systematic direction to the deployment of Lean in a complex enterprise? Can SE analytical methods provide insight into how best to select and evolve a Lean enterprise structure? Can lean organizational processes be assessed for risk and tailored so as to be robust to potential instabilities in their operations or environment? Some work is already underway to address questions in this research stream through the Enterprise Architecture research area in LAI.

The final possible research stream involves a true fusion of Lean and SE. To some extent, by fortunate coincidence, research in LAI to date has involved this approach. Lean/SE fusion research would likely be phenomenon-driven, where questions to be explored may include: "what combination of Lean and SE practices will yield best lifecycle value for a given program?"; "how does a change in the degree of complexity affect that combination of practices?"; and "how does departure from established products or processes affect the combination of practices?" The strengths of this approach to research are that it can allow exploration of the knowledge domain to "map the terrain", and may lend itself to the development of contingency models that explain how standard procedures and practices behave under novel circumstances. A potential weakness of this approach is that if it is left to be driven by phenomenological requirements alone, it may not address the field with enough structure to advance it. In fact, research in all three streams outlined here are welcome, and indeed important given the newness of the Lean SE paradigm.

Finally we note that there is considerable current interest to developing the body of knowledge for effective System of Systems Engineering (SoSE). There is reason to believe that such principles could have roots in Lean SE. SoSE will be more complex than SE due to the larger number of systems, interfaces, enterprises, and stakeholders involved. Just as Womack's 5 principles of Lean Thinking given in Table 2 serve as a effective baseline for Lean SE, the 5 Lean Enterprise Value creation principles given in Murman, et al[4] could provide a baseline for lean thinking for SoSE.

6.0 Summary

In this paper we propose that SE and Lean, while different in many ways are oriented towards the same overall objective of creating value for the stakeholders of complex systems. We believe, based on research to date, that there is significant potential benefit from a fusion of the two perspectives into a new research and practice paradigm, Lean SE. We've shown that value stream thinking can be a powerful tool to help inform what problems are more important than others to tackle. This applies in research as well as in practice. Much of what we have discovered during the course of this research implicates the importance of organizational and management processes in the realization of complex systems. Advanced tools and processes can be important enablers of high performance, but neither can overcome dysfunctional organizational behaviors. Particularly in the domain of complex product systems and the complex organizational systems that create them, neither the Lean nor the SE perspective alone are likely to address issues of management, coordination, and interaction as well as they might when combined.

In order to realize significant gains from the merger of SE and Lean, the conduct of the research may need to conform more closely to the phenomenon of Lean SE: the scope of analysis must expand to encompass significant portions of product lifecycle value streams, and the stakeholders engaged in the research and practice must be able to bring multiple perspectives to the endeavor. While more challenging than research in traditional disciplines, we believe the payoff will be worth the effort—bringing significant advances in the knowledge and practice of both SE and Lean, and the emergent whole of Lean Systems Engineering.

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