Abstract

Many aerospace and defense system affordability issues can often be traced back to early systems engineering and supply chain decisions that placed a premium on size, weight, functionality, and business “price to win” targets only to find that recurring production cost targets could not be met due to inadvertently “designed-in” manufacturing inefficiencies. To address this problem, there is a significant need for industrial engineering and supply chain analyses to be integrated into early systems engineering activities to ensure that systems are optimally designed to meet both internal “producer” and external “user” stakeholder requirements. This paper will describe a novel approach for integrating manufacturing and supply chain considerations into the systems engineering process through the development of an industrial V-model which mirrors the conventional product V-model. The benefits of adopting this integrated product-industrial system design framework is that it provides a structured hierarchical concurrent engineering approach to balance conflicting performance and producibility requirements that impact system affordability at each stage in the system design and development process.

1. Introduction

The development of affordable products has become a critical issue impacting the aerospace and defense industry as the cost of developing new generations of systems continues to spiral out of control, with these same problems very likely to occur on future programs as well unless something fundamentally
different is done in the ways these complex systems are designed and developed. The severity of the affordability problem in the defense industry is highlighted by a recent Government Accountability Office (GAO) study which found current defense acquisition programs are experiencing on average 42% growth in research and development costs from original estimates, have an average delay in delivering initial capabilities 22 months behind schedule, with 42% of the programs also reporting a 25% or more increase in unit acquisition cost [1]. Commercial aerospace system development programs are also experiencing these same affordability problems. For example, the Airbus A380 superjumbo jetliner launched in 2000 and the Airbus A400M military transport plane launched in 2003 were both years behind schedule and billions of dollars over budget, with Airbus attributing these overruns due to the inability to price “risk” [2]. Delays are also plaguing the Boeing 787 Dreamliner launched in 2004 which was expected to revolutionize the way airplanes are manufactured using new advanced materials and a daring global manufacturing network where nearly 80% of the airplane is fabricated by outside suppliers [3], with the first flight taking place nearly two years late [4].

These examples illustrate how significant shifts in the industrial base landscape driven by globalization and the exponential growth in aerospace and defense system complexity over the last two decades has created an environment where the effective application of systems engineering principles and advanced modeling and simulation based risk analysis approaches are being recognized as critical needs. In fact, many production issues can be traced back to early architecture decisions that placed a premium on size, weight, and functionality which resulted in designs that could not be efficiently and economically produced due to overly complex manufacturing processes, excessive yield fallout, and scrap and rework levels that were not factored into the original “should cost” estimates. Figure 1 graphically illustrates this point and shows the results of a study that found 70% of the life cycle costs are locked in by the time conceptual design is completed, where only 8% of actual development funds have been spent [5]. Clearly the largest, and only, opportunity to make step change improvements in producibility and affordability is in the front-end of the systems engineering process as product and industrial base requirements are being analyzed and initial product design and supply chain concepts are being developed and refined.

![Fig. 1. Life Cycle Cost Commitment as a Function of the System Life Cycle](image)

There is much debate about what the systems engineering discipline is and is not, and if current systems engineering methodologies and tools are adequate to cope with the complexity of 21st century system development. Amidst all the debates, one thing that can be agreed on is that systems engineering has many trans-disciplinary applications and layers that can be used to model the physical products being designed, the larger systems they will be integrated and/or interact with, the business systems that must bring them to market, the industrial systems that must produce and sustain them, and the socio-economic systems that they and we are ultimately part of [6-8]. A supply chain is also a system, or a system of systems in many cases, yet there has been little work done to look at extending basic systems engineering principles to help design and analyze the complex multi-tier supplier network required to support and sustain the physical product over 30+ year life cycles and understand its behavior and robustness due to changing global business and industrial base dynamics.
In addition, modern aerospace and defense supply chains are large and complex, involving many sub-tier suppliers over diverse geographical regions. There is no doubt that the supply chain of the 21st century will continue to be a constantly changing and evolving dynamic entity, with new “systems engineering” approaches required to design and dynamically model multi-tier global supply chains and the new risks they introduce that conventional supply chain management approaches fail to address. The present paper is not aimed at solving this complex problem, but rather is an initial attempt at developing a top level framework to bring a “systems thinking” perspective of how one might approach designing robust and resilient supply chains to cope with the complexities and dynamics of the 21st century global industrial base. The framework also provides a structured approach to optimizing products for producibility at all levels in the system hierarchy that leverage product and process modeling and simulation techniques for manufacturing. The authors hope that this treatise will stimulate additional research into methods such as these to improve aerospace and defense global product realization practices.

2. Systems Engineering Methods for Manufacturing Enterprise Design

There are many representations of the systems engineering process used to develop large-scale complex systems, with the most common hierarchal representation based upon the well known V-model [9]. A representative product V-model is shown in figure 2 which drives a top-down approach to design and a bottoms-up approach to the build, integration, and test activities including validation of the as-built system against specifications. The V-model was first developed in the late 1980’s and several variants of it have been used for software development [9], automotive systems engineering [10], electronic system integrated hardware, software and logistic activities [11], and even the field of epistemology to support research design and process validation [12]. In all of these examples the main benefits of the V-model is in the hierarchical thinking and structured design and validation approach it drives in which complex problems are broken down into smaller more manageable problems at different levels of abstraction. It is recognized by the authors that the V-model has limitations and it is not the intent of this paper to address these, but rather to demonstrate the application as a framework to drive a structured hierarchical way of thinking about how to design and analyze a manufacturing enterprise. This includes the identification of trade-offs that need to be balanced with the product design at various levels of abstraction and design definition to optimize the overall affordability of complex aerospace and defense systems and products.

The proposed industrial V-model framework shown in figure 3 follows similar logic to the product V-model, starting with the voice of the “producer” which is analyzed and translated into industrial flow down requirements that could include manufacturing cost structures, strategic material use, make/buy content, globalization, and other goals as well as learning curve assumptions and production ramp rate and cost targets. These requirements are then used to define alternative manufacturing enterprise

Fig. 2. Product V-model

Fig. 3. Industrial V-model
architecture concepts using baseline value stream maps for existing “similar to” products that define industrial base footprints, proposed factory development and/or consolidation strategies, risk sharing partnerships and strategic alliances, emerging market supplier capabilities, commodity procurement strategies, historical supplier performance metrics, etc. The main focus at this level of abstraction is on driving the identification of industrial constraints and key performance parameters (KPP’s) that are considered critical and essential to the development of the manufacturing enterprise that must produce and sustain the product over its lifecycle. This includes the development of analytical figures of merit that characterize the ability of alternative manufacturing enterprise concepts to meet critical business objectives and identify any industrial base gaps and required development needs, with the main output from this phase the top level go-forward manufacturing enterprise footprint development strategy.

Once the top level manufacturing enterprise architecture has been defined and the major risks areas identified, the next step in the industrial V-model framework is to design the detailed supply chain and/or factory layout structure for each architecture element. At this next level of abstraction, the KPP’s associated with the enterprise architecture are decomposed into lower level requirements such as technical capabilities, contract compliance, customer service levels, and quality and delivery performance targets. The type of industrial information typically available at this stage in the process could consist of regional supplier process capabilities, supplier maturity ratings, sole versus dual sourcing options, supplier source selection criteria, proposed factory layout and expansion plans, specialized manufacturing capabilities and workforce skills, demand forecast and capacity constraints, etc. required to guide more detailed supply chain and/or factory design and analysis activities. Figures of merit for this next level down in the hierarchy must also be developed so that alternative supply chain and/or factory layout concepts can be evaluated, down-selected, and refined based on their ability to meet the allocated flow down requirements and identify key supply chain gaps requiring additional development. The main output of this stage of the design process is the definition of the go-forward supply chain and/or factory layouts, including the identification of risks that impact the ability to meet product rate, cost, quality, and delivery requirements.

Once all of the suppliers and production lines within the factory have been defined, the next step in the industrial V-model framework is to design, develop, and optimize the manufacturing processes and ensure that the appropriate quality controls are in place to sustain production at the desired rate, cost, and quality levels. At this next level of abstraction the previous set of KPP’s are further decomposed into lower level supplier and factory manufacturing requirements that process capabilities can be evaluated against, such as capacity and throughput, lead time, yield, price, inventory and safety stock buffers, etc. Information typically available at this stage of the analysis consists of production line capacity constraints and monuments, equipment and cell specific process capability data, “similar to” part manufacturing work instructions, routing sheets, etc. Figures of merit for this next level down in the hierarchy must also be developed so that alternative process and quality control concepts can be evaluated, down-selected, and refined based on their ability to meet the allocated flow down requirements and identify any process gaps requiring further development. The main outputs from this step include the detailed work instructions and process specifications that define how the individual items will be manufactured, including unit product cost, yield, lead time, set-up, and inventory/safety-stock targets that will be monitored.

The bottom of the V-model framework culminates in the individual items that define the bill of material (BOM) under configuration control being manufactured, with the right half of the V-model defining how specific metrics at each level in the manufacturing enterprise hierarchy will be collected, analyzed, and monitored to ensure manufacturing performance objectives are met and sustained, including control plans and recovery strategies. For a complex aerospace and defense system such as the F35 Joint Strike Fighter or Boeing 787, the industrial base required to produce and sustain the product can be as complex as the product itself, with the proposed industrial V-model framework providing a structured hierarchical way of breaking down the manufacturing enterprise design and development process into smaller manageable elements. An additional benefit is that it drives a proactive approach to
define and link key metrics that will be used to monitor, diagnose, and sustain the overall manufacturing enterprise performance across multiple supply chain tiers. The description provided here is not aimed at tackling the problem of defining specifics of how one would go about designing and analyzing a large manufacturing enterprise, but rather provide a new way of approaching this challenging problem using a “systems thinking” perspective.

3. Integrated Product-Industrial V-model and Trade-Off Optimization

Whereas the product V-model provides a structured hierarchical approach to define product design, development, and validation activities that maximize value to the “user”; the industrial V-model allows the same structured approach to be applied to the design and development of the manufacturing enterprise to maximize value to the “producer”. A common problem in aerospace and defense system development is balancing “user” needs that include product price and performance (size, weight, power, efficiency, etc.) requirements with “producer” needs that include profit and business performance (cost, quality, delivery, inventory, etc.) requirements. By performing the product and industrial design and development processes concurrently one can start balancing and trading-off requirements between product design and manufacturing so that value to both can be maximized. One way to visualize this is that the two V-models are mirror images of one another, with activities in both performed concurrently as one moves from left to right in the systems engineering process. Figure 4 shows the integrated product-industrial V-model framework to illustrate the concept.

Fig. 4. Integrated Product-Industrial Development V-model Framework

One of the benefits of looking at the problem in this manner is that it acknowledges the strong interdependence of design and manufacturing activities and the importance of balancing and trading-off conflicting “user” and “producer” stakeholder needs and requirements early and continuously throughout the product realization process. It also provides a structured process to drive manufacturing all the way to the left in the product realization process. This enables manufacturing considerations to be included in the requirements analysis process to ensure optimum product and manufacturing enterprise architectures.
are selected and matured in parallel, thereby allowing manufacturing concerns and risk to be identified and proactively mitigated as the design evolves. One caveat, however, is that analytical modeling and simulation tools must be available in the systems engineering tool kit to analyze both the product and industrial design concept to vertically link the left sides of the integrated V-model and allow trade-offs to be performed. This includes quantitative product-centric design tools to ensure “users” requirements are met, as well as quantitative industrial-centric design tools for producibility to ensure “producer” requirements are met as early product and industrial engineering concepts are being evaluated.

It should also be noted that we are not advocating designing a new manufacturing enterprise for each new product, but rather that manufacturing enterprises and their supporting supply chains can be designed and analyzed using systems engineering approaches to help cope with the complexities of the 21st-century industrial base. One challenge with implementing the proposed approach, however, will be the fact that most supply chain management functions are organized around commodity families, engineering functions are organized around technologies/disciplines, and marketing functions are organized around product lines. Conway noted in 1968 that organizations are constrained to produce designs which are copies of their organizational communication structures [13]. Thus, in order for the integrated product-industrial V-model to work new communication structures and interface boundaries between design, marketing, and manufacturing will more than likely need to be defined.

4. Summary and Conclusion

In summary, an industrial V-model has been developed which provides a structured hierarchical approach to the design and development of the manufacturing enterprise that parallels the conventional product V-model using a “systems thinking” approach. When used in a concurrent engineering framework, the integrated product-industrial V-model drives the co-design of both the product and industrial base so that both “user” and “producer” needs and the associated flow down requirements can be balanced early and continuously throughout the product realization process. A main benefit of this approach is that it provides a hierarchical way of breaking the complex problem of global manufacturing enterprise design down into smaller more manageable sub-problems that are easier to solve and ultimately model. This includes the development and linkage of manufacturing performance health metrics that span across multiple supply chain tiers so that the impact of individual supplier performance on the overall supply chain health can be ascertained. The model also provides an architectural modeling framework that would allow system dynamic modeling techniques to be applied to supply chain problems to understand their transient and dynamic cost, quality, and delivery performance under a variety of internal and external forcing functions. More research is needed to advance the concept and implement into current systems engineering processes, but it is felt that systems engineering approaches such as these could help address the affordability challenges that the aerospace and defense industry currently faces.

Additional research is also needed to develop manufacturing modeling and simulation capabilities that support industrial engineering activities comparable to the design tools that exist for engineering performance analysis at multiple levels of the system hierarchy. This includes not only manufacturing process and supply chain modeling techniques, but also producibility models that predict product-process interactions being driven by product and process design characteristics at the component, assembly, sub-system, and system level. These analyses tools would enable systems engineers and design teams to identify producibility and manufacturing concerns during the “fuzzy” front-end of the design process and allow industrial engineering considerations to be incorporated into the trade space. An overview of such manufacturing modeling and simulation needs that could be used within the proposed integrated product-industrial V-model framework to enable these trades is described in [14-15]. Examples of product-centric producibility analysis tools developed by the authors for use during early conceptual and preliminary design activities is also given in [16], which could be used in the lower part of the proposed integrated product-industrial V-model to drive component level trades that optimize producibility and affordability.
Although not presented here, the authors have applied these tools in unpublished work to show how the proposed approach could be used to optimize the affordability of an acceleration switch for an inertial measurement unit (IMU), including its packaging and design of the supply chain used to produce it.

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