



# System of Systems Analyses of RTI International Metals' Boeing 787 Seat Rail Supply Chain

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**S**ystems engineering provides tools to effectively develop intricate systems as well as systems composed of systems. The use of systems engineering is becoming increasingly prevalent due to the methods ability to handle the increasing complexity of systems in modern society. Among these systems are today's global manufacturing networks, driven by recent trends in globalization. This work evaluates the development of a complex manufacturing network in comparison to principles of systems engineering to highlight areas that could have improved from the systems engineering methodology.

**Keywords:** System of systems, manufacturing network, complexity, risk management, systems engineering methodology.

## 1 Introduction

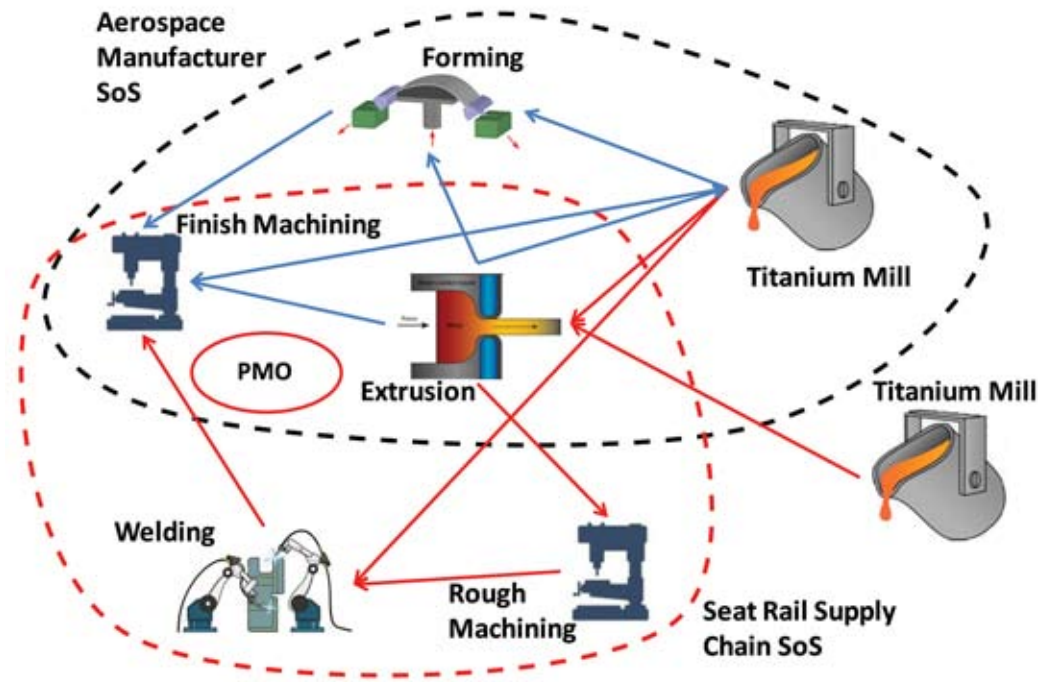
Within the aerospace manufacturing industry, there are multiple suppliers of finished machined metal components. A vertically integrated manufacturing company with a specialization in titanium is the source of this paper. The intent is to take system engineering methods for evaluating a system of systems (SoS) and apply this to the evaluation of this manufacturing system. This tool was defined by the

U.S. Department of Defense and is commonly used in integrated defense systems [1].

This analysis focuses on a manufacturing supply chain, which is a functioning SoS within RTI International Metals, Inc, Headquartered in Coraopolis, PA. The supply chain defines the manufacture of the seat rail, or sub floor framing, for the Boeing 787. This is a somewhat recent SoS development within the manufacturing company and provides insight into current systems engineering practices to be compared with published approaches. The functional model for the supply chain are depicted in Figure 1 that outline the production steps for the seat rail components.

Illustrated in the diagram of the SoS, the aerospace manufacturing company is depicted. The analyzed seat rail supply chain SoS is depicted with red flow lines. The chronology of systems in the supply chain are: extrusion, rough machining, welding, and finish machining. A level of complexity results because the rough machining and welding are not part of the aerospace manufacturing SoS.

In the discussion, the activity toward the establishment of the seat rail supply chain SoS will be examined in detail. This is partially contained within the aerospace manufacturing company SoS. These partially overlapping SoS create a complex dynamic in the operation of the SoS. Within the supply chain



**Figure 1:** OV-1 illustrating top level system interaction of the SoS involved in the seat rail supply chain SoS. Red indicates Seat Rail flows and SoS boundaries. Blue and Black represent the manufacturing company's flows and boundaries.

SoS exists the project management office. This is the SoS management of the supply chain and is mostly aligned with the finished machining individual system as they are considered the supply chain owner.

The SoS level key requirements present for the supply chain SoS are: deliver complete sets on time in full, minimize working capital, and maintain profit margins to within corporate goals [2].

## 2 Background

Systems engineering is the planning, organizing, integrating, and evaluating of individual systems into a SoS with a capability greater than the sum of the constituent systems capabilities [1].

In this evaluation, reference will be made to both systems and SoS, and the key differences should be known. A system is a related group of interacting elements that form an independent and unified whole entity. A SoS is composed of independent individual systems to form a larger system that delivers unique capabilities [1].

The governance of a SoS is more complex than for an individual system. Stakeholders exist for both

the SoS as well as the constituent system of which it is composed. Sometimes there exist conflicting interests among these stakeholders depending on if they represent a constituent system or the SoS. The negative result of this conflict is the reluctance to assign priority to tasks outside of the constituents system. It is common for the SoS to have objectives and resources; however, it is also common that individual systems possess their own management, funding, engineers, and development programs. This makes the governance of a SoS complex and difficult. In order for effective development and operation of a SoS, a collaborative approach must be taken by systems engineers to effectively govern the SoS [1].

There are four types of SoS: Virtual SoS, Collaborative SoS, Acknowledged SoS, and Directed SoS. These are listed in order of ascending dependency and centralized control. The seat rail supply chain SoS examined in this paper currently represents a collaborative SoS. In this way, the systems are completely independent and interact with little central direction to meet agreed upon purposes. It is the objective of this study to identify avenues to improve SoS oversight to the point that an acknowledged SoS can be developed. In this way, the constituent

systems would collaborate under a recognized SoS management while maintaining individual ownership and operation of their systems [1].

There exist seven core elements that define the activities of a SoS. These include: translating capability objectives; understanding systems and relationships; assessing performance to capability objectives; developing and evolving an SoS architecture; monitoring and assessing changes; addressing requirements and solution options; and orchestrating upgrades. The activities of a systems engineer operating on a singular system can be composed into 16 categories. These include: requirements development, logical analysis, design solutions, implementation, integration, verification, validation, transition, decision analysis, technical planning, technical assessment, requirements management, configuration management, data management, and interface management [1].

The application of these activities into the core elements for a SoS evaluation was generated for the manufacturing SoS as seen in Figure 2. In the depicted figure, the common systems engineering tasks that correlate the SoS activities are shown in gray. The horizontal axis represents common systems engineering activities for a system. The vertical axis represents the activities involved in SoS engineering. These applications are explored in detail within the paper.

### 3 Translating Capability Objectives

The formation of a SoS relies on the identification of needed capabilities. The systems engineers are then responsible for articulating this in technical level functions and requirements. A portion of this task is the prioritization and weighting of requirements to ensure best SoS behavior. The generation of capability objectives will depend on stakeholder needs, external factors impacting the SoS, and feasibility based on the SoS architecture, limitations, and functionality [guide].

When the manufacturing SoS is defining a supply chain, the primary objective is the production of a specific product. Along with this are the properties that the component or assembly must possess. This is translated into technical requirements to achieve the specific properties with the desired geometry. These requirements are typically generated by engineers familiar with the processing dynamics with

the individual systems in the company.

## 3.1 Technical Processes

### 3.1.1 Requirements Development

The translation of capabilities into requirements provides the foundation for the development of a SoS. This is often a dynamic process that refines through the development process. In many cases, requirements are specific to a manufacturing approach, and multiple requirement options may need to be produced so as not to limit solution options. The input of stakeholders must be taken and balanced to provide capabilities technically, practically, and affordably.

The manufacturing SoS will often need to determine the end customer needs for a required product. The technical staff receiving this stakeholder input would then translate this into technical requirements necessary to produce the product. In some cases, multiple production paths can be identified. In some instances, the customer has a more active role in defining the approach to manufacture and outlining of requirements. It is still common that some requirements will need to be generated beyond what is outlined by the customer.

In the aerospace manufacturer SoS, the individual systems maintain operational independence and often define their own requirements. The supply chain SoS also maintains requirements primarily geared toward satisfying customer and corporate stakeholders [2]. The requirements for the customer focus on quality, cost, and production rates. The company objectives address working capital, stakeholder value, and profitability. These SoS level objectives are not routinely communicated to constituent systems or collaboratively involved in their formation [2].

There is also opportunity for improvement with the collaborative development of technical requirements for the individual systems. A significant lesson learned occurred when a vendor in the initial seat rail supply chain could not meet a flowed down requirement. Rather than the SoS collaboratively working to resolve or mitigate the inability to meet the requirement, exceptions were taken for the requirement. The result was down stream product fallout, the cost of which was absorbed by the supply chain. This had significant impact on profitability, deliveries, and working capital [3]. This represents a significant opportunity for the manufacturing SoS.

		Technical Processes							Technical Management Processes							
		Requirements Development	Logical Analysis	Design Solution	Implement	Integrate	Verify	Transition	Decision Analysis	Technical Planning	Technical Assessment	Requirements Management	Risk Management	Configuration Management	Data Management	Interface Management
Core SoS Elements	Translating Capability Objectives															
	Understanding Systems and Relationships															
	Assessing Performance to Capability Objectives															
	Developing and Evolving an SoS Architecture															
	Monitoring and Assessing Change															
	Addressing Requirements and Solution Options															
	Orchestrating Upgrades to SoS															

Figure 2: Activity mapping of systems engineering activities to SoS elements for the aerospace manufacturer SoS.

### 3.2 Technical Management Processes

#### 3.2.1 Requirements Managements

The management of requirements is critical to meeting long term capabilities of a SoS. Requirements should be documented back to the end customer needs or industry specifications. The management of this requirement information is critical to the defining, assessment, and prioritization of customer needs for the SoS capabilities. This effort also highlights justification for critical requirements and allows robust decisions for requirements of the system as objectives change with time [1].

The seat rail supply chain SoS maintains requirements for individual systems labeled as key performance indicators (KPI). These requirements are managed by the SoS for the top level requirements. The management of constituent system requirements falls on the individual systems. A centralized management tool does not exist to compile all system and SoS level requirements or track them back to stakeholder or industry requirements [2]. This represents an opportunity to improve visibility and traceability of requirements throughout the supply chain.

#### 3.2.2 Risk Management

When addressing capability objectives for a system of systems, the risks associated with achieving these capabilities must be addressed. The level of risk associated with a capability will have some level of impact on decisions of capability feasibility or system modification to mitigate risk [1].

Prior to the start of a supply chain, gaps and weaknesses are evaluated for the supply chain. This is performed by the customer and high level technical staff within the manufacturing company. A key development that occurred in the SoS of the seat rail supply chain was the formation of a project management office (PMO) to oversee the SoS [4]. This was a key success as it provided the framework for effective SoS management for the supply chain.

#### 3.2.3 Data Management

The availability of system data plays a significant role in defining capability objectives. This data allows for informed evaluations in regards to systems capabilities and expectations. The robust collection, centralized storage, and practical accessibility of system data enables more informed evaluation and accurate requirements development based on desired objectives.

The manufacturing system has centralized data hardware; however, individual systems currently operate on separate networks. There is an effort to implement a centralized quality management system that stores important manufacturing data from all individual system on a central location [4]. This unified access will allow universal access to requirements and documentation associated with requirements. This would improve fidelity of the supply chain system of systems.

## 4 Understanding Systems and Relationships

A key component of development of a supply chain is the understanding of how systems interact and support the SoS functionality. This understanding also includes the identification of technical details pertinent to the operation of the SoS. A major key to developing an understanding of a SoS is the definition of the following: system boundaries and interfaces, resource relationships, requirement responsibilities, relationships in the development processes, identification of stakeholders and their impact, and constituent systems relationships [1].

There is considerable work toward developing the understanding of systems and relationships within the manufacturing company. The manufacturer operates based on supply chains that are established and put into operation. Upon initial setup, there are still some iterative improvements to be realized in the operation of the established supply chain. During establishment and operation, change authority often lies with the end customer. This presents challenges to implementing changes or improvements and most efforts to build development plans must be performed collaboratively with the customer.

### 4.1 Technical Processes

#### 4.1.1 Logical Analysis

Logical analysis provides the foundation for understanding a SoS by highlighting how each system supports functionality of the SoS. This is a technical task involving specific input and output parameters associated with each system [1].

In the manufacturing system, as is the case with many manufacturers, the individual systems represent organizations across the world acquired at different times. The recent acquisition of new entities represents a constantly changing set of relationships. Resources are devoted toward integration of new acquisitions, however, clear technical capabilities are not systematically distributed amongst the manufacturing system to foster systemic interactions [4].

A success of the SoS is that there are already resources devoted toward developing solutions optimized to the manufacturing SoS. This system wide logical understanding is localized within a portion of the organization in the technology development office. This is effective at establishing technical flows for a

defined system, but operational mapping is not systematically utilized. Improvements could be realized by producing detailed logical analysis of each system in the manufacturing system, in all aspects. This analysis could be extended by identifying additional possible new relationships within the manufacturing system and fostering them [4].

In the SoS of the seat rail supply chain, the lack of logical analysis to define the SoS overview resulted in the misappropriation of capacity. The understanding of constituent system contributions, lag times, and requirements was not factored into demand signals to the individual systems. This production signal became chaotic and resulted in unnecessary shifts in production and diminished capacity. This caused delays and bottlenecks throughout the supply chain [3].

### 4.2 Technical Management Processes

#### 4.2.1 Risk Management

A key task when developing the systems understanding for a SoS is identification of risk involved. The consideration of anticipated behavior of the SoS should be made. The systems engineer should also identify core functional paths, required changes due to conflicting constituent system needs, capacity constraints, technical constraints, and stakeholder behaviors in the SoS understanding.

In the manufacturing SoS, there are many aspects of operation which require risk mitigation. A major area of risk management is in system capacity. The use of production readiness assessments (PRA) provides the level of risk for each system and the supply chain in different elements of operation [2]. An opportunity for improvement could include the collaborative evaluation of the supply chain. This would ensure that all activity, beyond the activity associated with the supply chain, is accounted for. Historically, this has proven a painful lesson when the total capacity was overestimated by not accounting for activity outside the supply chain. This resulted in a delayed identification of the need for capacity expansion and delays [3].

#### 4.2.2 Configuration Management

The configuration management of SoS is primarily focused on the interaction of the constituent systems. The individual systems typically maintain their own

baseline processes and the systems engineer works with the individual systems to develop logical links between functionality of these systems. These logical links could also represent future links for SoS expansions.

The configuration management for the metal manufacturing system is a key task in understanding systems and relationships. The pressures of globalization, corporate acquisitions and mergers, as well as expanding new technologies in the titanium industry, are certain to influence changes to the structure of the manufacturing system [5, 6]. The ability to redraw the SoS relationships in detail as individual systems are added, subtracted, or modified, will be central to effective operation of the manufacturing system. A formalized system is not in place to aid the process of change. Currently, with system changes, the process is entirely manual and resource intensive [2]. The formalization of the understanding of system relationships and functionality could reduce resources required to develop or change supply chains in the future. This systemic best practice could also include lessons learned to prevent reliving of mistakes with new SoS.

#### 4.2.3 Data Management

The systems relationships are pivotal for understanding of SoS behavior. In order to facilitate greater understanding of systems interactions, the documentation defining the SoS should be centrally stored and accessible by constituent systems. This information would consist of systems relationships, functionality, interfaces, data flow, development plans, and shared attributes.

The centralized management of data from all individual systems plays a key role in the understanding of the system behaviors. Many of the behaviors of systems need to be characterized with data analysis to clearly define system inputs and outputs. Currently, many individual systems operate separate data systems, but significant effort has been put forward for a unified data management system, in the quality module [4]. The global collection of data and documentation throughout the manufacturing life will greatly increase the knowledge and visibility of relationships and performance characteristics within the manufacturing system. This will also provide statistical quantification of inputs and outputs for use in defining systems relationships.

#### 4.2.4 Interface Management

The understanding of systems relationships in a system of systems is a direct contributor in defining interfaces between constituents. The interdependencies and critical flow of information dictate what information is transferred between constituent systems and what format it is in. How the individual systems utilize the transferred information in its functionality should also be taken into account in the analysis of the system [1].

In the seat rail supply chain SoS, the amount of data transfer is small in comparison to some system of systems. There are two systems being developed to facilitate interfaces between constituent systems. The interactions in regard to production parameters are to be handled by a VSMIS system [2]. This is to streamline interaction and tracking throughout the chain. The management of technical production information will be handled by the quality module tool [4]. The identification of the key data transfer involved in the SoS interfaces should be the result of the mapping of the system relationships [1]. This is a key opportunity for system improvement.

### 5 Assessing Performance to Capability Objectives

The operation SoS, as well as constituent systems, rely on the effective evaluation of performance driven by implemented decisions. The development of measures to determine performance relative to performance objectives is an effective way to quantify the outcome of a system change or current state of operation. These metrics should be developed in collaboration with the technical individuals from constituent systems to ensure key parameters are chosen as metrics to capture performance. Metrics should also be chosen to be compatible with future SoS changes and expected improvements [1].

In the manufacturing SoS, there are considerable amounts of performance metrics evaluated. The majority of SoS metrics are related to production rates, customer feedback, and the interaction with systems within the supply chain and outside the manufacturing company. The drive to reduce operating inventory and support lean manufacturing drives continuous adjustments to production rates and priorities based on needs and inventory levels. The development of technical metrics at the individ-



ual system level including mechanical, metallurgical, and geometrical properties and are necessary to ensure that operations were performed within defined operating limits [2, 4].

## 5.1 Technical Processes

### 5.1.1 Validation

The assessment of performance is vital in the validation process following a SoS change. As the SoS is developed or evolved, considerable assessment is required to determine if performance matches expectations for the planned change. This establishes the degree of improvement and dictates whether more change is warranted [1].

In the establishment of a supply chain SoS, where iterative refinement is common, the continuous assessment of performance is crucial. The performance data provides the validation for all iterative changes and justification for future changes and directions [4].

In the seat rail supply chain SoS, routine validation is performed in respect to production characteristics. The evaluation of machine and manpower capacity is performed to validate production performance [2]. An opportunity for the supply chain is to extend this global awareness to technical aspects of performance, which is currently handled by constituent systems [4]. This would enable comprehensive understanding of performance and enable SoS level development.

## 5.2 Technical Management Processes

### 5.2.1 Decision Analysis

The use of decision analysis in regards to performance assessment aims to evaluate that relevant data is being collected and evaluated for trends. The systems engineers should be assessing if critical data is being collected at the proper times and in the correct ways. Considerable evaluation of performance should also address the emergence of secondary performance impacts from a change, determination of root causes, and generation of alternative approaches.

In a manufacturing system, considerable decision analysis is performed by the technical individuals within constituent systems. The iterative refinement process, when defining a manufacturing process, uses thorough assessment of performance to drive refinement through much iteration until production is optimized [4].

The supply chain SoS does not formally utilize decision analysis to define paths to assess performance. Performance is currently assessed through standardized industry tools providing many aspects in the quantification of performance. An area for improvement, that is currently being explored, is the augmenting of these tools to include collaboratively defined metrics for the individual systems in the supply chain [2]. This should provide a more comprehensive evaluation of supply chain as well as constituent performance.

### 5.2.2 Technical Assessment

The assessment of performance is also used to evaluate the degree of technical progress a SoS is making. As changes are made to the SoS, the degree of effectiveness can be collected and used to determine if the desired effect is realized and that behavior is conducive with anticipated operating principles [1].

In manufacturing system SoS, this is most seen in the implementation of new technologies within constituent systems. The upgrade or addition of new equipment has thorough technical assessment and validation prior to full operation in the aerospace industry. Many technical parameters of production equipment have to be compared with theoretical datum or analog equipment to determine that performance matches technical plans [4].

The manufacturing system SoS does not have a formalized assessment method specifically aimed at technology. The main assessment tools currently examine entire systems within the SoS [2]. The grading of technology against production requirements represents a major opportunity to provide a basis to drive technological innovation to be most effective with development resources.

### 5.2.3 Risk Management

The assessment of performance is a key component of evaluating the level of risk in a SoS and to determine the effectiveness of mitigation steps. There is also a level of risk associated with the assessment of performance that engineers must address based on possible impact and mitigate this if possible [1].

In manufacturing systems, the receiving of false control and performance data can have significant impact on SoS performance. The failure of information during critical heat treatments and metalworking

can render produced components unusable and can accumulate rapidly if left unnoticed.

A major lesson learned in the seat rail supply chain SoS occurred because of the lack of risk management with performance assessment at the start of the seat rail supply chain. The lack of collaborative developed understanding of risks and roles resulted in false production signals and the failure to capture this error in the system. The result was extensive over production of some components of the delivered sets [3]. The use of collaborative risk management methodologies should help to identify pit falls and establish assessment tools to capture these conditions.

#### 5.2.4 Data Management

One of the centralized processes of assessing performance is the centralized collection and access to data. This becomes an accumulated body of knowledge to be drawn from in many circumstances to guide decisions. The centralized storage allows behavior evaluation for the constituent systems as well as the cumulative SoS [1].

In the SoS of the aerospace manufacturing system, work is currently being done to collect data on a unified production tool [4]. Where there still exist opportunity is to compile this data into useful formats that represent key metrics and establish access to this information both at the supply chain level as well as the constituent system level.

## 6 Developing and Evolving a System of Systems Architecture

With the definition of system requirements, logic flow of the systems, and definition of performance metrics, the architecture of the SoS should be developed. This effort encompasses the functional contributions, technical needs, internal and external systems relationships, communication infrastructure, and risks of the SoS. In some application, up front sensitivity analysis helps to identify critical aspects of a SoS architecture based on system output variability. Much of the system architecture is constrained by the functionality of the individual systems [1].

In the manufacturing system, this operation is often shared with the end customers who own the entire supply chain. The individual systems are also well established prior to their incorporation into the

supply chain [5, 6]. The architecture will capture and manage the operation of the entire SoS, both inside and outside the company. This will be the vehicle that drives the effective operation of the supply chain SoS. This effort is also not heavily supported by the end customer as the identification of functional steps. The change of the functionality within the constituent systems in a supply chain SoS is limited in most cases. The interaction of each individual system in multiple supply chains restricts the ability to change functionality to address an individual supply chain SoS unless all supply chains accept the change concurrently.

### 6.1 Technical Processes

#### 6.1.1 Requirements Development

The interpretation of stakeholder inputs into requirements is the driver for SoS evolution. The architecture must adapt to address the requirements. Changing requirements forces changes in the SoS. It is common to include requirements in a SoS for the enabling of future functionality needs. This defines an architecture that may not fit existing SoS structure, but will enable less cumbersome upgrades as functionality is incorporated.

In the supply chain SoS, the customer must be involved in all work that has an impact on finished product properties. Historically, the customer has driven most major supply chain architecture decisions and will likely maintain significant presence in these decisions [4]. However, recent changes in the industry indicate a shift of primary ownership toward the tier one suppliers. These primary suppliers have significant authority in supply chain requirements development [5, 6]. The ability to define supply chain requirements presents an opportunity to compete for tier one status on more supply chains in the future.

#### 6.1.2 Logical Analysis

The logical flow of SoS architecture is critical for changing the system. The identification of SoS operational environment, functional mapping, information and material flows, trigger conditions, expected behaviors, and span of operation will be the basis for understanding of the impact of evolving the system.

There was a significant lesson learned with the failure to adequately map product flows and trigger conditions in the seat rail supply chain SoS. The



lack of trigger conditions necessary to synchronize production between individual systems in the supply chain resulted in the individual systems optimizing their own operation. This resulted in a push model across the supply chain. The result of this was a severe swelling of operating inventory and congestion at bottlenecks of the supply chain [3]. The establishment of logical mapping of the entire SoS, as well as anticipated upgrades, is a significant opportunity to improve operational coordination.

### 6.1.3 Design Solutions

The generation of alternative design solutions based on requirements and logical analysis is a central role of a systems engineer. The engineer must outline how the systems will work together by defining functional components, behavioral principles, and relationships. The generation of solutions that will be useful over time is critical. This is done by understanding where change is needed and likely. A design solution for the SoS will be generated by the systems engineer. The design engineers for the constituent systems will be responsible for designing sub-systems to meet their requirements. This operation will be iterative until the SoS and constituent systems designs are compatible.

In the SoS of the aerospace manufacturer, the customer will have significant influence on all design solutions created to manufacture components [4]. This will prove an additional challenge as all designs must be iteratively developed with them as well. The ability to design solutions for manufacture is a new responsibility being realized by top level suppliers in the aerospace industry [5, 6]. This presents an opportunity to expand the role and ownership of supply chains across the industry and leverage vertical integration across the supply chain.

## 6.2 Technical Management Processes

### 6.2.1 Design Analysis

The use of decision analysis is the basis for selecting the best design solution from the multiple design options generated. This evaluation of the design options relative to performance metrics should also examine flexibility, change timeline, funding requirements to enact and upgrade, and adaptability to change [1].

In the seat rail supply chain SoS, limited work has

been done on solution analysis [2]. This represents an additional opportunity to strengthen skills necessary to be a tier one supplier in the evolving aerospace industry [5, 6].

The development of a technical plan to evolve a proposed design option toward its final envisioned architecture should be included with assumed strategies and mitigation strategies to support the plan. This should be developed in coordination with the technical plans of the constituent systems [1].

The planning of technology evolution of supply chain is a critical ability for a SoS. The manufacturing system SoS maintains a research and development budget and personnel within the manufacturing SoS [4]. Where there is opportunity for improvement is in supply chain technical planning for supply chains. This would provide a tool to effectively implement development resources to support major production lines.

### 6.2.2 Requirements Management

With all SoS that evolve over time, a system for the management of requirements is critical. The centralized tracking and documentation allows for changing requirements to be verified against their original justification regardless of the date of change [1].

In manufacturing systems, the need for requirements documentation is critical. The loss of traceability to requirement justification requires costly redevelopment of requirements and opens the SoS for errors from replication after the fact [4]. This is very difficult because usually some portions of decisions are internal to the end customer only and regeneration is very difficult [2]. Currently, top level requirements are managed by the system engineers for the seat rail supply chain and flowed down within the production orders. A formal requirement management tool to ensure continuity of requirements is not currently being utilized in the supply chain [2]. This represents an opportunity for improvement and could be incorporated into the developing quality module tool.

### 6.2.3 Risk Management

Risk management helps to systematically mitigate costly failures associated with the changing of SoS architecture. At this stage, risk management should focus on key functional risks, constituent system

synchronization risks, issues with inflexibility of constituents, technical risks, and resistance to change [1].

In a created supply chain SoS, there is a considerable amount of risk to evolving the architecture. Essentially, the system has to be re-qualified technically and from a capacity standpoint [4]. The failure to address risks upfront proves costly from redesign and late delivery standpoints.

In the supply chain SoS, quarterly risk analysis is performed on the supply chain architecture to analyze potential scenarios and risk mitigation techniques for production rates [2]. The expansion of risk management to incorporate technical risks associated with the supply chain architecture represents an opportunity to improve the robustness of risk mitigation.

### 6.2.4 Configuration Management

As the SoS evolves, considerable amount of attention has to be given to configuration management. Through the changes to the SoS, the critical information flow and data acquisitions should continue to ensure seamless system operational integrity. This becomes more difficult with significant modifications to system architecture and should be addressed by the systems engineers [1].

Plans exist in the seat rail SoS to develop a configuration management tool to assist the development of other SoS. This would include anticipated customer expectations, lessons learned, and identified best practices to aid the development of this and other supply chain SoS [2]. This represents a major opportunity to improve supply chain development effectiveness.

### 6.2.5 Data Management

The validation of changes to a SoS architecture requires the availability of critical data prior to and after changes are made. This information is required for SoS evaluation as much so as internal to the individual systems. This critical data includes architecture drivers and tradeoffs, architecture representations, control logics, operating principles, risks, key metrics, and technical plans [1].

In the aerospace supply chain SoS, the centralized management of data is also key to operation. The high level of interdependency and qualification rigors merit high levels of data collection. The development

of a data management tool to operate within the SoS architecture is a critical task. The development of the quality modules role as a data management tool for supply chains represents a major success within the manufacturing system SoS [4].

### 6.2.6 Interface Management

The interface between constituent systems relies on common communication mechanisms. The addition or replacement of systems within a SoS requires this to be revisited to ensure communications of key information is preserved and functionality is not lost in the SoS [1].

In the manufacturing system SoS, the amount of data flow is much lower during operation. The style of data is also less important as much of this can be converted to other formats, such as drawings and collected data [4]. The purposeful planning of interfaces when the supply chain is created ensures that data is transferred completely and conveniently to reduce lost time and effort [1]. The development of clear communication protocols between constituent systems represents an opportunity for improvement by allowing minimal wasted time and effort for inter-system transactions.

## 7 Monitoring and Assessing Changes

A key activity with all SoS is addressing changes outside the SoS, which could have an impact on functionality and performance. This could be an environmental change as well as a change to individual subsystems. It is up to the system owners to address these in the system through intervention to alleviate the effects or attempt to mitigate their negative impacts. Additionally, the constituent systems often evolve independent of the SoS, and the impact of this must be continuously revisited and evaluated. The uses of technical meetings, between shareholders from individual systems, are common to identifying anticipated future developments and collaboratively evaluate their impact on the SoS [1].

In the titanium manufacturing supply chain, this is a collaborative effort since much of the change authority is owned by the end customer. These potential influences must be carefully evaluated and communicated to the tier one supplier so effective changes and mitigations can be coordinated. There

has been considerable impact on this industry in the recent past with raw material shortages causing delays in deliveries [5].

## 7.1 Technical Management Processes

### 7.1.1 Decision Analysis

As the SoS environment evolves, there will be a need to implement changes. Decision analysis will provide the basis for evaluating options to implement for the SoS. These changes can encompass new and enabling technologies, changing SoS objectives, or customer demand shifts. Analysis should be performed with criteria with the objective of optimizing the SoS and the constituent systems [1].

In the aerospace manufacturing SoS, the reaction to changes is driven by the end customers. Though input is common, the end customer is involved with large changes in any supply chain [4]. Top level individuals are involved with decisions regarding significant changes in the seat rail supply chain. The immediate upstream and downstream systems are often included in discussions to identify impacts [2]. An opportunity for improvement lies in the development of a collaborative forum to evaluate impact from external factors on all constituents in the supply chain as well as the SoS as a whole.

### 7.1.2 Risk Management

The evaluation of risk associated with external environmental change is a critical metric for determining if action is required. The reduction or risk through mitigation techniques is also important information in monitoring change.

The supply chain SoS utilizes operating environment changes in the quarterly risk analysis. The analysis of anticipated impact and likelihood for possible scenarios in the external environment assist the determination of potential risk to the supply chain. This result motivates a course of action [2].

### 7.1.3 Data Management

The collection of data associated with constituent system changes and external environment changes aids the tracking and evaluation of the SoS situation. The impact of actions taken in the past is also useful in guiding future decisions [1].

A success of the aerospace manufacturing SoS is that quantitative data is tracked for customer de-

mand [2]. There exists opportunity for improvement in how this data is managed and extracted for use in the systems of the SoS. A lesson learned in the seat rail supply chain occurred when the production requirements for other supported supply chains for an individual system were not evaluated. The cumulative increase warranted capital investment to expand capacity. The evaluation of each supply chain individually did not indicate this. This resulted in a delayed ordering and temporary lack of adequate capacity [3].

### 7.1.4 Interface Management

The assessment of change in a SoS addresses the changes in interface between individual systems. This must be managed to ensure communications are not lost between systems.

Development of an interface management tool, VSMIS, has the aim of streamlining interaction between systems. The amount of data transfer between constituent systems in the seat rail supply chain is small compared to some SoS. One example of an emerging interface management change, is a growing demand for 3D digital scanning of components to demonstrate conformance. This aids in decision making for machining systems, however, this requires costly equipment and time for the metalworking constituent systems [4]. The periodic evaluation of customer interfaces is an area for improvement to ensure seamless interaction with the supply chains.

## 8 Addressing Requirements and Solution Options

When considering the operation of a SoS, there are needs and requirements of the system that must be prioritized and addressed. A number of solution options would need to be generated to attempt to meet the system's needs and requirements. A key aspect of this activity is understanding the individual systems from a technical, organizational, and constraint perspective and applying this when evaluating solution options. The requirements managers from the individual subsystems should be engaged in the derivation and division of subsystems requirements in order to balance needs within the SoS [1].

The outcome of this effort is the formation of a technical plan to address the requirements with a SoS. This may also indicate the need to develop

upgrades to the SoS architecture if the existing SoS is incapable of delivering to the requirements [1].

In the aerospace manufacturing SoS, the customer has played a primary role in designing of supply chains. [4] Current trends in the aerospace industry are indicating shifts toward tier one supplier owned supply chains. [5] The ability to address various supply chain options in relation to requirements has not been formalized due to the lack of need to thus far dictated by the end customer [4].

## 8.1 Technical Processes

### 8.1.1 Requirements Development

The generation of technical requirements based on requirements from stakeholders is a primary focus when addressing requirements. These technical requirements are interpreted and conveyed to individual sub-systems. This can be complicated by the presence of multiple options within the SoS. The development of requirements should also account for constituent system resources, human capital, equipment, and funding necessary to meet requirements. This can result in an iterative process to develop requirements.

In the manufacturing SoS, there are often multiple alternatives when developing a supply chain SoS. The requirements for competing systems can also have very different technical requirements.

Limited requirement development is done at the SoS level for the supply chain SoS [2]. Much of the detailed requirements are created by the constituent systems [4]. A significant opportunity for improvement exists by developing a method for collaborative development of requirements for the systems as well as the SoS. This will allow requirements to be optimized to a specific solution design.

### 8.1.2 Design Solution

The development of design options based off of generated technical requirements is a key function for the systems engineer. Ideally, a number of alternative design options are created, of which the most ideal solution is chosen. It is also noteworthy that the most ideal solution can dictate the extension beyond the SoS [1].

In the manufacturing SoS, the generation of design solutions involves many of the stakeholders. The end customers typically oversee developmental ef-

forts and designs of supply chains. In more rare cases, suppliers will undertake developmental efforts in the anticipation of future work. This involves significant risk and assumptions of acceptance. The qualification processes in the aerospace industry are very intensive. It is common that design options are generated between established and proven processing technologies [4].

In the seat rail supply chain SoS, the initial top level solution was determined by the customer [4]. The customer maintains a significant presence in development of design solutions, however increased collaboration between systems has increased involvement with the customer in proposing solution options [2].

## 8.2 Technical Management Processes

### 8.2.1 Decision Analysis

The activity of decision analysis drives the evaluation and selecting of alternatives amongst design options. This analysis is based off the answer to two key questions:

1. Which requirements can be practically implemented in the next iteration?
2. What are the options for their implementation?

The development of answers to these questions can be very complex endeavors requiring extensive knowledge and rigor. It is also important to consider the available opportunities that involve a variety of different systems [1].

When evaluating options for a possible supply chain in a SoS, it is important to know costs and difficulties associated with various processing operations. Typically, operations will be based on a combination of mature existing processing technologies, as high levels of uncertainty surround the qualification of new processing technologies. The project manager will also have to look beyond the realm of the SoS. It is common to have a supply chain that is not completely encompassed within one manufacturing SoS [2].

The current state of much of the decision analysis lies with the end customer or lead integrator. The supply chain provides input into the decisions, but decision analysis lies within the end customer [4]. This stifles the SoS evaluation as one stakeholder is driving the supply chain architecture. The incorporation of all stakeholders in decision analysis provides

opportunity to balance all stakeholder objectives in an ideal solution [1]. The expansion of collaboration with constituent systems and stakeholders is an opportunity for improvement of design outcomes and stakeholder relationships.

### 8.2.2 Technical Planning

Upon the selection of a preferred design option, a systems engineer develops a detailed technical plan to outline the scope of the SoS. This plan should account for resources, schedules, milestones, and costs. This should also incorporate input from iterative negotiations with engineers from constituent systems [1].

The aspect of technical planning faces the same complexity that decision analysis experiences to address solution options. The customer will be involved in major supply chain alterations [4]. In smaller scoped improvements, the level of customer involvement will be less. Currently, there are plans intended to develop a collaborative forum to evaluate systems and develop technical plans for improvement [2]. This is a major opportunity for improvement of constituent systems with a global perspective of SoS requirements.

### 8.2.3 Requirements Management

The management of requirements during the assessment and selection of design options is typically a multi-level task. As design options are iterated, the requirements for the supply chain and individual systems may change, and these changes must be tracked back to industry specifications. The individual systems typically track their own requirement changes, and the systems engineer will track the changes for the supply chain. The use of a tracking tool aids the synchronization of requirement changes into a unified system [1].

Currently, the manufacturing SoS does not have formalized tools for management of requirements across a SoS, though plans are in place for the development [2]. The central management of all constituent requirements represents a major opportunity for improvement. This establishes system requirements traceability back to design information and analysis performed at the time of solution option evaluation.

### 8.2.4 Risk Management

The evaluation of risk for all design options is an important factor in a design decision. The amount of risk that a design option presents directly impacts the likelihood of failure. Options can present risk based on uncertainty of root causes of behavior, requirements to change existing systems, and implementation of design options [1].

In the supply chain SoS, there are existing risk management methods for the existing SoS [2]. A major opportunity is to extend this into a formal method to be utilized at the time of supply chain option evaluation. This would identify risk factors that may lead to one solution option over another.

### 8.2.5 Configuration Management

Configuration management involves using sound practice to ensure the consistency of a product's attributes. These practices are identified as functional baselines and incorporated into standard operating procedures [1].

In the manufacturing system, the use of quality management tools are implemented into operating procedures. Planning would be done to adapt and expand existing quality checks to encompass the critical parameters of the proposed supply chain SoS [4]. An opportunity for improvement lies in the task of identification of key quality and business attributes for all proposed solution options. This would allow more understanding of the involved aspects of each solution and a framework for configuration management at the time of developing the system architecture.

## 9 Orchestrating Upgrades

In the realm of SoS, the orchestration of upgrades involves addressing system requirements through a change. This activity involves the facilitation, monitoring, and coordination of changes being implemented. This effort typically will require iterative planning with independent systems to arrive at a phasing plan that is acceptable to all individual systems in the SoS. In addition to planning, this will involve the alignment of resources to support the critical path of project implementation. Typically a SoS upgrade occurs when the involved systems agree on a technical plan to address SoS requirements [1].

Several external factors must be continuously accounted for in the execution of upgrades that may affect the outcome. These include technical issues, design changes, budget cuts, program changes, regulatory changes, or a reprioritization of development efforts. These types of changes require the continuous revision of the technical plans to incrementally address requirements [1].

In the manufacturing SoS, the enacting of a supply chain within the SoS can be considered an orchestrated upgrade. A subset of systems within the SoS, and some outside of the SoS, are aligning themselves to address the unmet requirement of producing a specified product for a customer. Each individual system will have their requirements involving their contribution to the finished product. The supply chain, which becomes a SoS within the manufacturing SoS, will also have requirements to ensure a comprehensive production and quality throughout the supply chain.

## 9.1 Technical Processes

### 9.1.1 Implementation

Typically implementation is primarily performed by individual systems under the guidance and support of the systems engineers. During this effort, the timing, steps, methods, and backwards compatibility should be addressed for the involved systems [1].

In the supply chain SoS, the compatibility is critical to individual systems in the sense that existing production lines must be supported as well as the new supply chain activities. Major infrastructural changes to systems would have an impact on other product families but may be necessary to support the new supply chain. With all changes, a series of requirements for all production will surface involving process qualification, operational methods, and quality assurance. The implementation of the seat rail SoS was overseen by a project management office formed at the announcement of the supply chain formation [4]. There lacked formalized procedures for implementation of the changes, and activities were manually implemented by qualified technical individuals. A major success is the initiation of the development of a procedure outlining this activity to aid future supply chain formation [2].

### 9.1.2 Integration

The integration of the individual systems into a single unified SoS is a key function in producing beginning to end functionality of the SoS. This is done by the systems engineer collaboratively with all systems. Since the individual systems will likely have competing requirements, it is key that the integration activity be coordinated by the systems engineer independent from any individual system [2].

The manufacturing supply chain integration will involve the development of communication systems between systems to facilitate communication, technical developments, production requirements, and delivery of physical products. This is a collaborative effort to ensure that an agreed upon flow of critical information and product results [1]. The involvement of all constituent systems in discussion to form the supply chain is a method to improve results in the future. The failure to involve all constituent systems during the modification of finished component requirements resulted in a partial SoS adjustment when changes were not adequately pushed down the supply chain [3]. Moving forward integration efforts would aid in promoting improved SoS behavior and improvements.

### 9.1.3 Verification

The verification process is a continuous effort to ensure that the upgrades are enacted according to plan. The establishment of key parameters of each system should be identified and tested. This step involves a continuous evaluation and possible modification to plans to ensure that system requirements are met. This also includes the communication of results to other systems so modifications to other systems plans can be made as necessary to ensure requirements of the SoS is met [1].

This is a critical operation of the manufacturing supply chain. As with many manufacturing systems, there is likely to be some level of iterative refinement of the processes of production. In some instances, a great deal of development occurs beyond the initial plans set out for the supply chain because of the complexity of many of the processing operations, making finite design infeasible. This step is a critical step and can take extended periods of time in some cases. This effort is primarily contained within individual systems as of present [4]. A success lies



in the existence of extensive verification procedures with changes to systems. This is also performed by qualified technical individuals with multi level sign offs. [4] An avenue for improvement lies in the distribution of results from the verification effort to constituent systems in a SoS may allow other systems to adjust to optimize the SoS.

#### 9.1.4 Validation

The validation step involves proving that the SoS operates as desired. This is often a limited effort until the end of the upgrade as end to end simulation or verification is limited until development is more concrete. Often this functional testing is focused on areas with the greatest risk [1].

In the manufacturing SoS, this entails limited production through the supply chain. This often brings to light issues around integration on top of issues with individual systems. This task is typically not performed with simulation, as simulation tools effectively accounting for all aspects of production have not proven practical [4]. An area for improvement lies in the development of more formalized documentation of initial production and procedures for doing so. This should also be shared among the entire supply chain to allow collaborative decision making.

#### 9.1.5 Transition

The transition activities in systems of systems focus primarily on support and sustainment of the SoS. In the supply chain SoS, this operation would entail operations surrounding the production ramp up. This is also critical, as many issues will not surface until significant production rates are achieved. In the roll out of the 787 production, it was soon discovered that titanium raw material suppliers were not keeping up with demand, and supply chain shortages arose [5]. An area for improvement lies in the global evaluation of supply chain resources [3]. The accounting for all aspects, including competition for resources and capacity across the industry, will aid the effective support of operation of future developed supply chains.

## 9.2 Technical Management Processes

### 9.2.1 Decision Analysis

Many decisions must be made during the orchestrating of an upgrade that affects the implementation

of the technical plan. The key operation in the decisions analysis is the balancing of needs and requirements of constituent systems. This is particularly important when upgrades do not go as planned and modification of other systems is required to achieve SoS requirements. These changes will draw heavily on knowledge of system interdependencies to define new requirement windows [1].

In the supply chain SoS, there is an inherent interdependency as the production output of one system is the input for another system. Variation or error in one system has the potential to affect all downstream operations of the supply chain SoS. A key aspect of decision analysis is requirements optimization for the SoS. This ensures that individual systems, in an effort to simplify their operation, do not impose impractical requirements on other systems that cause unnecessary production rejections or deviations. The failure to optimize the whole SoS will result in the entire SoS failing to perform [1].

Currently, decision analysis involving a supply chain is conducted by the project management office or office of technology commercialization. This is performed by technical individuals familiar with the constituent systems [4]. An area for improvement would directly involve the constituent systems in the decision analysis to optimize the system during an upgrade.

### 9.2.2 Technical Assessment

The technical assessment for a SoS is the examination of the change implementation of the constituent systems. The evaluation of system inputs and outputs relative to critical criteria should be performed routinely by the systems engineers. This step also includes the addressing of changes when progress is not being made [1].

In the manufacturing SoS, this operation is dependent on the level of innovation of the supply chain. In the majority of product supply chains, industry specifications govern high level operating parameters that ensure production outputs are in the desired form [4]. With more complex production supply chains, industry specifications may be insufficient and must be expanded and evaluated to ensure desired material properties. In these cases technical assessments are performed by the qualified technical personnel within the manufacturing SoS [4]. An area for improvement could lie in the development of formalized methods to reduce time required to

perform an assessment.

### 9.2.3 Requirements Management

The management of requirements through the orchestration of an upgrade provides effective documentation for the production of components and traceability to ensure quality. As changes are made during the implementation, changes to requirements may be required and should be documented back to their original sources. The updating of the information systems housing the requirements will ensure that the supply chain operates on the same set of requirements after the upgrade [1].

The aerospace supply chain SoS requires documentation of met requirements throughout the entire production chain. The finished components properties are the accumulation of all processing steps throughout the SoS, and all critical requirements are necessary at the final stages for quality assurance upon delivery. The iterative development of the production process in some processing systems makes requirements management difficult and critical to ensure that requirements are being met by the system [4]. An area for improvement lies in the development of a centralized requirements management tool to maintain greater visibility of any requirement changes during upgrades.

### 9.2.4 Risk Management

The identification of risks associated with a SoS is an effective mitigation method for preventing undesired outcomes in implementation. The evaluation of risk level and contingencies for risks threatening the performance of a SoS or the constituent systems reduces late stage failures [1].

In the manufacturing supply chain, risk management is a complex undertaking. The manufacturing systems themselves have numerous factors affecting their operations [4]. An area for improvement learned during the implementation of the seat rail supply chain implementation was the need for collaborative identification of risk. The risk associated with a welding vendor was not identified in other systems. The result was higher levels of product fallout and lost capital [3].

### 9.2.5 Data Management

The data management associated with orchestrating upgrades focuses on documentation of changes throughout the process. The availability of the detailed information about changes provides insight into decision analysis and future changes [1].

The manufacturing system will rely on the project managers and engineers to document changes and upgrades to the current state of the SoS. The storing of these changes on a centralized network with access by all constituent systems and involved parties will allow improved decision making criteria for similar changes in the future. There does not currently exist centralized data networks and universal access across the supply chain SoS [2]. The incorporation of this data into the developing centralized data network, quality module, would be an avenue for improvement.

## 10 Conclusion

The analysis of the seat rail supply chain SoS has revealed several areas where SoS methods are in the process of being formed independent of the results of this analysis. These developments are the result of a number of lessons learned through the development process of this SoS.

There were also a number of areas for improvement to improve the ability to form and manage the supply chain SoS. Given that shifts are beginning to occur within the industry, supply chain development and collaborative design are to be expected behaviors of top level suppliers [5, 6]. An improved system engineering ability in relation to SoS will position the manufacturing SoS as a collaborative partner with end customers. It will also allow influence in supply chain architectures and an ability to leverage vertical integration and extensive industry expertise to maintain competitive advantages in the industry.

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