A Distributed Simulation Approach for Modeling and Analyzing Systems of Systems

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A DISTRIBUTED SIMULATION APPROACH FOR MODELING AND ANALYZING SYSTEMS OF SYSTEMS

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ABSTRACT

Certain business objectives cannot be met without the interaction and communication between different systems. An interesting concept called system of systems (SoS), which aims to describe this interaction between systems has been gaining attention in the last few years. In this paper an extensive review of the literature is performed to capture the main characteristics associated to this concept in order to propose a new, more complete definition. This paper also proposes the use of distributed simulation through the High Level Architecture (HLA) rules to model and simulate systems of systems. We illustrate our idea with two different examples; a simplified supply chain network of a computer assembly and an aircraft initial sizing scenarios. The paper concludes with a discussion of some of the significant advantages distributed simulation could offer over traditional simulation for the analysis of such complex systems.

1 INTRODUCTION

The rising concept of system of systems describes the interaction between different independent and complex systems in order to achieve a common goal. Businesses today have come to the conclusion that their success depends on the successful interaction between different groups of systems together.

The supply chain framework provides a standard representation for information sharing that enables the ease of communication between different software applications, firms, management information systems, etc. The approach followed in this work will facilitate the development of integrated, adaptive and interactive models with different levels of abstraction for simulated trade-studies of performance and cost over the solution space for evolving customer requirements. Through a complete awareness of cost factors, this approach will support decision making early and throughout the design and manufacturing life cycle.

The paper is organized as follows. Section 2 presents an extensive investigation of system of systems definitions in the literature. Essential and desirable characteristics are identified for distributed simulation purposes and a new, enhanced definition is proposed. Sections 3 and 4 expands on two examples to illustrate the key characteristics of our definition in modeling SoS through the HLA. In Section 3 we describe a simplified supply chain of a computer assembly. The supply chain concept was chosen for this paper because it involves numerous dependent and complex entities working towards a common goal – bringing a quality product to the customer at the lowest cost.

The second example described in section 4 utilizes the system of systems concept for new product design. This example seeks to illustrate how using the HLA, distributed simulation could be used to enhance interoperability of heterogeneous computing environments while significantly reducing the negative impact generated by geographically separated design teams.

We conclude this paper with further discussion of some key points presented in this paper (Section 5) and future work in terms of cost modeling.

2 LITERATURE REVIEW

For the past decade, the concept of system of systems has generated a lot of interest. There is not however, until today, a wide definition of this new concept. Different au-

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thors proposed definitions of a system of systems for military applications. Manthorpe and William (Manthorpe and William 1996) focused on this concept being used for information superiority in military applications. They believe a military system of systems should focus on interoperability of command, control, computers, communications, information, intelligence, surveillance and reconnaissance systems. Pei and Richard (Pei and Richard 2000) defined a system of systems as the integration and optimization of different systems to enhance performance of future scenarios in the battlefield of a war. In their paper (Sage and Cuppan 2001), Sage and Cuppan claim that the majority of five characteristics, operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development, should be satisfied in order to view a system as a system of systems.

In their definition, Kotov and Vadim (Kotov and Vadim 1997) focused on the private enterprise sector. They defined a system of systems as an interaction between complex systems forming a large scale concurrent and distributed system. Their definition stresses that a system of systems should fulfill several important requirements such as cost effectiveness, throughput, flexibility, responsiveness, security among others.

Carlock and Fenton (Carlock and Fenton 2001) also defined system of systems focusing on information systems for the private sector. They defined a system of systems engineering should focus on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis.

Lukasik (Lukasik 1998) studied this concept with the goal of educating engineers to appreciate different systems and systems interactions. He defined a system of systems as the integration between different systems to ultimately contribute to the evolution of the social infrastructure. (Keating et al. 2003) defined system of systems as "Meta-systems that are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography and conceptual frame".

Crossly of Purdue University defined the concept of system of systems as a dynamic entity describing the large scale integration of many independent, self contained systems to satisfy a global need. Dynamic because new systems are added and current systems are replaced or removed easily. The department of defense differentiated between a system of systems and a family of systems. They define a system of systems as a set of interdependent systems connected to provide a certain capability. A family of system is defined as a set of interdependent systems connected to provide different capabilities.

From the study of the above literature we concluded that to take full advantage of distributed simulation for modeling systems of systems, most of the characteristics associated to this concept are essential (X), while a few of them are desirable but not critical for modeling (+). We summarize our study in Table 1.

2.1 System of Systems Proposed Definition

Definition: *A system of systems is a system formed by several systems that interact with each other, in a heterogeneous environment, to achieve a goal; with the following restrictions:*

- *At least some of the systems can act "independently"*
- *At least some of the systems were designed "independently"*
- *Heterogeneous environment (interoperability is a way to mitigate the negative effects of being Heterogeneous; there are two types of interoperability: Functional and Technical).*

3 A SIMPLE SUPPLY CHAIN SCENARIO

The supply chain scenario was chosen for this paper because it involves numerous dependent and complex entities working towards a common goal – bringing a quality product to the customer at the lowest cost.

Table 1: Systems of Systems Characteristics

Characteristics / Author	Independent Systems	Distributed Systems	Meta Systems	Complex Systems	Integration / Interaction	Global Need (Mission)	Inter operability
Pei (2000)					X		X
Lukasik (1998)					X		
Kotov (1997)		X		X			
Manthorpe (1996)							X
Keating et al.			X	X			
Crossley	X				X	X	
DoD	X				X	X	
New Definition	X	+	+	X	X	X	X

The HLA is integral to the example because it facilitates interoperability amongst components that are designed using different tools (Arena and AnyLogic) running on distributed computers. Such design flexibility has many advantages technologically, financially and politically (Imbrogno, Robbins and Pieris, 2004). The next two sections described the scenario and the use of HLA. A detailed description of each of the Arena and AnyLogic models then follows.

3.1 A Simplified Supply Chain

According to Ching (2001), the traditional logistics chain is made up of six stages: (1) suppliers' suppliers (sources), (2) suppliers, (3) processors (manufacturers), (4) distributors (or wholesalers), (5) retailers and (6) consumers. Our model groups these stages into three sets according to their inputs and outputs. The first group is the supplier, or source. Suppliers take orders as input and output deliveries. Because suppliers act as the source to the system, they neither receive products or place orders. Inventory is created internally. Our second group consists of manufacturers. This group accepts orders and deliveries as input and outputs orders and deliveries. The final group is the customer which accepts deliveries and outputs orders. The customer is equal and opposite to suppliers in the system, i.e. they generate orders internally and introduce them into the system and consume products without accumulating inventory. All models must contain at least one supplier and at least one customer. Any number of processors can be used including none at all. Figure 1 shows how such a supply chain federation can be developed using both the Arena and AnyLogic simulation packages combined with a HLA run-time infrastructure. When a customer or processor creates an order, it is sent to the RTI via an adapter or gateway so that it can be received by the preferred producer. The producer then fulfills the order according to its internal model logic, which takes into account parameters such as inventory and production rates. Finally, finished goods are sent downstream to the proper customer, once again via the RTI.

3.2 High Level Architecture (HLA)

Grouping by inputs and outputs emphasizes the system of systems approach to supply chain management. Expansion, both horizontal and vertical, is facilitated by the High Level Architecture's (HLA) promotion of interoperability and object reuse. This allows for simulation models to be developed much more rapidly than before (Borshchev, Karpov and Kharitonov, 2002) and at the same time reduces the requirement of companies to share sensitive information that is necessary when building. With HLA, each company's simulation can run on a dedicated server using open, closed or black box accessibility. In an open system, third parties would be able to alter the logic of a model. In closed systems, third parties can observe the system as it operates, but cannot make changes. Finally, in a black box system, the third party enters the input and accepts the output without understanding the mediating process.

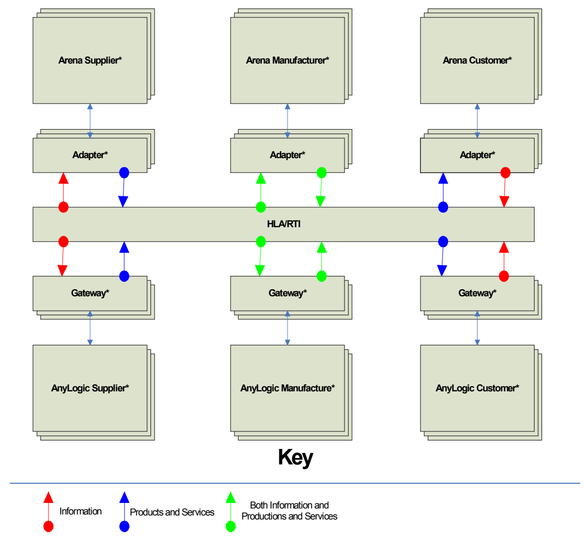

Figure 1: Supply Chain Example Layout

3.3 Model Details

In order to demonstrate the benefits of utilizing the system of systems concept to implement a distributed simulation, in comparison to constructing a monolithic supply chain model, we developed a simple Supplier, Manufacturer and Customer models in both Arena and AnyLogic (professional simulation modeling tools) that interoperate over a network.

HLA rules are used to define relationships among federation components (federates) to specify an interface specification that describes the way simulations interact during operation. It is also used to specify an object model template that specifies the form in which simulation elements are described.

Three stages constitute a supply chain for computer assembly. A manufacturer stage with two manufactures (Dell, IBM) represented by M1 and M2, a supplier stage with four suppliers (CDW, TigerDirect, Ingram Micro and TechData) represented by S1, S2, S3 and S4. Suppliers S1 and S3 are responsible for sub assembling the motherboard, CPU and RAM. Suppliers S2 and S4 sub assemble the chassis, the hard drive and the CD ROM. This gives each manufacturer the option of selecting from two suppliers for each subassembly. The third stage is the customer who chooses to purchase a computer from Manufacturer 1 or Manufacturer 2. The customer has the option of ordering from Manufacturer 1 or Manufacturer 2. Both systems are competing to win the customer's purchase. Figure 2 shows two possible SoS formed once a customer has placed an order. As can be seen, a supplier (S1 in Figure 2) could belong to more than one system.

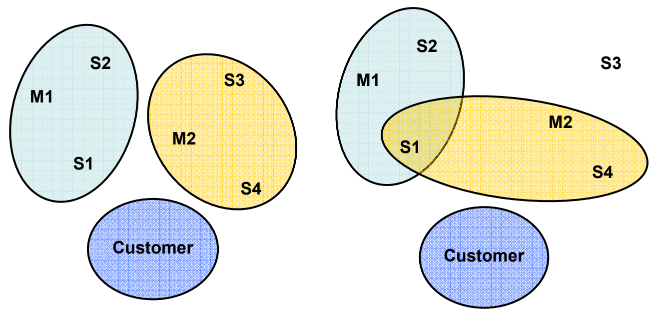

Figure 2: Models Interaction and System Formation in the Supply Chain

The models operate interdependently by sending two types of messages: Orders and Deliveries. Order messages travel up the chain based on demand generated in the customer model. Deliveries flow down when sufficient inventory has been produced by suppliers and manufacturers. Demand can either be generated randomly in the customer model using a timer object or based on a schedule. Once created, the order message is sent to one of the manufacturer models where it sits in the order queue, awaiting sufficient supply. When a delivery message is received, demand is decreased by the specified amount.

The manufacturer models receive orders from the customer and create a delivery if there are enough computers in the inventory. The rate of production in the manufacturer is determined by a discrete event simulation. The process consists of subassemblies arriving from suppliers and being inspected. If inspection is successful, the parts are assembled into a computer, inspected again and placed in inventory; if either inspection is unsuccessful the parts are returned to the supplier. An order is sent to suppliers when the number of subassemblies in stock falls below a certain threshold. The supplier process is similar to that of the manufacturer, however suppliers do not place orders, instead their stock is regenerated automatically.

3.4 Model Objectives

The goal of this example was to demonstrate the capabilities of the system of systems concept rather than analyze a supply chain. However, a number of simplifications were made to this supply chain: The inventory control policy in the Arena models, for instance, simply generates products if there is sufficient material. The AnyLogic models are slightly more intricate as they produce until inventory (finished goods – number on order) equals a certain threshold, at which point production halts. The process begins again when inventory falls below another, lower threshold. Other simplifications made include randomized demand pattern, no explicit lead times, no transportation lead time, and no cost considerations.

The simple structure of the simulation models created in this example can only allude to the potential of a SoS application to supply chain management. In future work, more complex implementations will need to be substituted in order to produce realistic results (Venkateswaran, Son and Kulvatunyou, 2002 and Wang, Xu and McGinnis, 2005). The substitution is a straightforward process so long as the new systems adhere to the interface format standards of its predecessor (Chong, Lenderman, Gan, Duarte, Fowler and Callarman, 2004), but performance is likely to suffer. In these cases, time management becomes extremely important, including the tradeoffs between optimistic and conservative policies. Time management in distributed simulation systems is discussed in (Fujimoto, 2003, McGinnis, 2004 and McGinnis, 2005). The distributed factory simulation case study of Wang, Xu and McGinnis (2005) is promising, however their implementation of the optimistic-conservative synchronization scheme uses specific information about the system being modeled. More generic solutions need to be discovered for SoS to achieve acceptable fidelity and performance. Figure 3 extends the supply chain design of Figure 1 into a more complex supply network.

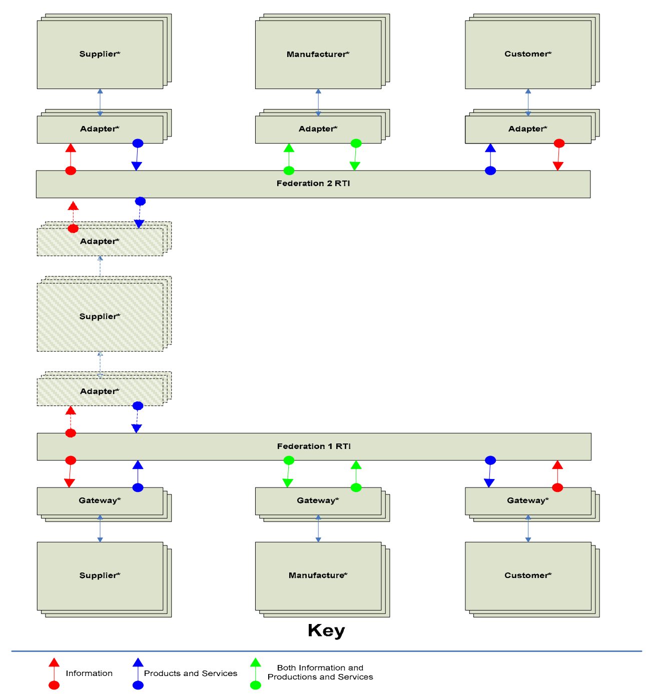

Figure 3: Multiple Industry Supply Network Sharing a Common Supplier

In this case, supplier federates are members of two otherwise distinct supply chains each with independent and unrelated demand patterns. One may think, for instance of an aluminum mill which fulfills orders to both canning and bicycle manufacturers. By taking advantage of object reusability and interoperability supply chain simulations can be built that are larger, more accurate and easier to build.

4 AIRCRAFT WEIGHT ESTIMATION SCENARIO

The Center for e-Design <http://www.e-designcenter.info> pointed to the fact that today's computer aided design systems (CAD systems) lack the capability to incorporate the conceptual design stage of a product or the ability to accommodate direct imposition of multi-disciplinary preferences and constraints (functionality, manufacturability, safety, etc.). These shortcomings take on their real significance when one considers that more than 70% of the life cycle costs of a product are consumed at the design stage. In their article, Reed, Follen and, Afjeh (Reed, et al. 2000) discuss the multiple benefits web-based modeling and distributed simulation through component architecture such as the HLA and CORBA (Common Object Request Broker Architecture) could bring to the aircraft design process. They stress that for an efficient design process, fully-updated data from one discipline must be made accessible to the other discipline without loss of information. Along with the Lack of interoperability between software, the heterogeneity of computing environments and, design groups that are geographically separated, it is the failure to identify early the interactions between disciplines which causes design processes to become less efficient. However, while the authors limit the use of distributed simulation at the preliminary stage (An aircraft design process is generally composed of a conceptual, preliminary and, detailed stage), which is the second stage of an aircraft design process, we believe its use could be extended upstream, to the conceptual stage, where the feasibility of a particular design is either confirmed or rejected. In the feasibility study, the mission of the aircraft, in terms of payload requirements, range, capacity, traffic frequency and more are defined. Given the enormous costs of developing a new airliner, ensuring that a design is feasible during the conceptual stage is crucial before committing to next phase, the preliminary design. Our second scenario seeks to illustrate how capturing these mission requirements from the customer, as they evolve, and monitoring the interactions between the disciplines involved in the early design process could be facilitated by extending the use of component architecture such as the HLA.

4.1 Federation Objective

In defining the problem space for this example, two specific criteria were defined. First, the example should depict a real-world situation, which would help illustrate the benefits of distributed simulation, such as system's interoperability. Secondly, the problem should present technical and engineering challenges which could be achieved in a reasonable amount of time and with moderate effort, given our expertise with distributed simulation and the HLA. Since the simulation of the preliminary and detailed design stages of an aircraft was tackled elsewhere (Reed, et al. 2000), our objective was to focus on the aircraft conceptual sketch stage by simulating the takeoff weight estimation process.

4.2 Federation Conceptual Model

While relatively straightforward for typical commercial aircrafts, initial takeoff weight estimation is an unavoidable process in aircraft design, depicting its importance. One of the major benefits of this process is that it quickly assesses an approximate weight penalty from some desired performance characteristics.

In order to faithfully represent this stage of the aircraft design life cycle while considering the characteristics of the aircraft manufacturing industry we mentioned earlier, an integrated systems' view of the whole process was adopted. By carefully defining each system, as well as each system's objectives and functionalities, a federation representing a system of multiple systems could be built. Our conceptual model calls for each system to be represented by a single federation member.

4.3 Federation Participants

Figure 3 is a top level view of our federation. It contains five federates: (1) Engineering Design Team, (2) Aerodynamic Model, (3) Propulsion Model, (4) Weight Model and (5) Initial Sizing Model. The objectives and functionalities of each are described below.

- <u>Design Team Model</u>: We use the commercial off-the-shelf simulation package ARENA 8.01 to develop this federate. It simulates the customer and designers who determine the need for an aircraft. Their main function is to establish the desired performance levels such as maximum range, payload weight and, cruise speed, just to name a few. All the performance requirements specified by this model are sent to the Initial Sizing Model which we described later.
- <u>Aerodynamic Model</u>: This federate is developed using AnyLogic, an object-oriented, HLA compliant simulation package. As its name indicates, its objective is to determine the most desirable aerodynamics characteristics for the performance requirements published by the Design Team Model. However, as can be seen in Figure 3, there is no interaction between the two models. All communications are maintained by the Initial Sizing Model.
- <u>Propulsion Model</u>: This federate possesses the same functionalities of the Aerodynamic Model.

However, its main objective is to propose the best propulsion solution for the desired aircraft performance measures. The main information published by this model is the specific fuel consumption (SFC) of a particular engine at different stages of the flight envelope. It is also developed in AnyLogic.

- Weight Model: The takeoff weight of an aircraft is determined by combining the estimated contribution of each phase (or mission) of the flight envelope (Climb, cruise, landing etc.). Based on inputs received from the Initial Sizing Model, the purpose of the Weight Model is to estimate those contributions. This model is also developed in AnyLogic.
- Initial Sizing Model: This federate is the knowledge base of the federation. As shown in Figure 3, any information that circulates in this federation is either produced or processed by this federate (with the exception of the interaction between the Aerodynamic Model and Weight Model). This federate has four distinct functions: it interprets any information published by the Design federate as it becomes available, provides to each of the other three federates the information they need to perform their tasks, captures any outputs of each of those models as they become available in order to estimate the takeoff weight and sends that estimation back to the Design federate.

4.4 Systems' Approach Benefits

We described, from the perspective of a system of integrated systems, the process of estimating an aircraft takeoff weight. While this example may prove simple and straightforward, it stresses that adopting a system of systems approach to a problem forces one to think carefully about what should be considered a system. In an aircraft conceptual stage, where multiple parties, from the airliner, to the manufacturer and contractors interact, the particular task of defining what the individual systems should be can be difficult. However, our model also shows that significant benefits may be obtained with this approach, possibly offsetting its shortcoming.

First, this approach favors people-machine interaction over a people-people interaction. If our model was to be applied in the real world, the people would be located in some or all of the following models: Design, Aerodynamic, Weight and Propulsion. The Initial Sizing Model on the other hand would have no people as it is a purely intelligent, knowledge base model which would have been developed previously. This is a benefit as it reduces the negative impact of geographically separated people.

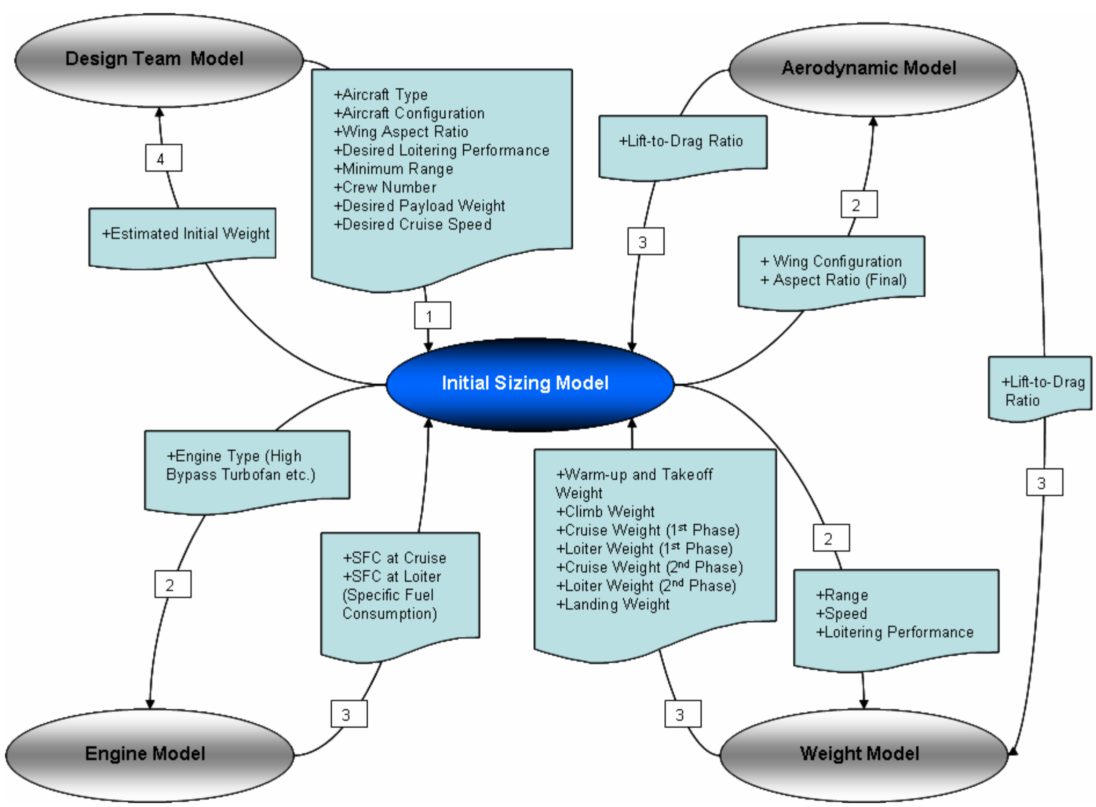

Figure 3: Model Interaction for the Aircraft Takeoff Weight Example

Second, this system oriented approach promotes reuse of its components, particularly of the knowledge base. Once designed, this model could be used as often as necessary with full confidence in its consistency between projects.

5 DISCUSSION

In illustrating the flexibility distributed simulation offers in modeling systems of systems, the two scenarios presented previously also point to the critical importance of identifying what constitutes a system. In the supply chain case a real system is composed of the following three components: a manufacturer and two suppliers. Each system is defined only once an order has been placed by the customer. Therefore, as presented, we designed a federation of components, as each federate models a component. This implementation differs significantly from the aircraft sizing scenario where the federation described is a federation of systems, as each system is modeled as federate.

It results from these implementations that in modeling systems of systems there is at least two phases which should be handled carefully: The accurate identification of each real system to be modeled and, the establishment of the degree of flexibility the SoS model should offer. Implementing the supply chain as a federate of components rather than a federate of systems showed a clear advantage distributed simulation can offer over traditional simulation techniques in terms of flexibility. On the other hand, while one can find software perfectly able to perform the tasks of the aircraft sizing scenario (Raymer 2006), the point was to illustrate the advantage distributed simulation could have for the conceptual design stage of a product, requiring the interaction between heterogeneous platforms and people.

6 CONCLUSION

Academia, the Department of Defense, and private enterprises are recognizing the importance of the SoS concept to create products that would satisfy their customers. This concept is aimed at understanding the interoperability between the different systems and at providing a means to rapidly adapt to changes. Although the concept is fairly new, numerous attempts have been made to define it. In this paper, a review of the literature for the various characteristics currently associated to SoS was performed, complementary or and conflicting characteristics (if any) were identified to attempt to enrich the definition of this concept.

In this paper, two scenarios were constructed and modeled to illustrate the advantages distributed simulation could offer in modeling complex systems. The future inclusion in both scenarios of cost models which are currently being developed will further establish the superiority of distributed simulation and the HLA for cost management and processes optimization in SoS. We believe that this future stage will allow for the design of a roadmap for future directions of cost ontologies, architectural mappings, and process cost analysis.

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