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Opportunities for Innovation in a System of Systems Framework

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***Abstract*— This paper examines various theories of innovation and sees how they apply to a system of systems framework. Systems of systems present an unusual challenge for innovation theory because some of the basic rules of the theory are broken by the system of systems paradigm. In particular, systems of systems are often deployed to solve complex problems that have a pressing need. However, pressing problems that require top system performance typically require an integrated solution – a solution where one entity controls all the components. By definition, a system of systems administrator does not control all the components and, indeed, may have control of none of them. This paper reviews various theories of innovation and applies them to an example that has previously been proposed for a system of systems.**

I. Introduction

System of systems is a new and rapidly growing field of systems engineering. While quickly advancing technologies often represent fertile grounds for new ideas, system of systems have further attributes that make them particularly interesting from an innovation viewpoint. One of these characteristics is that a system of systems, by its very nature, is a non-optimized solution to a problem. This paper uses theories of innovation to examine opportunities Systems of Systems (SoS) engineering presents for engineers, entrepreneurs, innovators and companies to develop new products, services and processes.

There are many different and often incompatible ideas about what a system of systems is. For example, Jamshidi [1] lists six definitions and notes that several more can be added to this inventory. Maier [2] proposed a set of characteristics of a system of systems that is often quoted in the literature. These characteristics include: 1) operational and managerial independence of individual systems; 2) geographic dispersion of systems; 3) presence of emergent behaviors in the overall system (due to interactions between the components); and 4) evolutionary development of the overall system over a period of time. Other characteristics that are sometimes used to describe a system of systems include self-organization, adaptation, autonomy of component systems, dynamic connectivity of constituent systems and interdependence of components [3]. Examples of areas where a systems of systems framework has been noted include: space exploration, healthcare, sensor networks, services, electric power systems grid, renewable energy, transportation, environmental management, military management and others [1]. Of these, some were purposely designed as a SoS, while others developed naturally, with no overall design plan.

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In terms of innovation, some of the above characteristics are more important than others. This paper uses a simplified characterization of SoS: a System of Systems is composed of two or more component systems that are combined to achieve an end goal. These component systems are all optimized for a purpose other than the SoS goal, and are not necessarily designed to work with each other. Moreover, a SoS designer has little or no control over the function of the component systems. An example may help clarify this definition. Suppose a company wants to ship a valuable part to a plant overseas. If they use a commercial airline to fly the part to another country and then use a commercial trucking company to transport the part from the airport to the plant, this would be a SoS because the airline and trucking company are independent. If, however, the company sent the part via FedEx, this would not be a SoS because FedEx is an integrated company that controls both the air and land transport of the part.

One underlying theme in the above definitions seems to be that the authors all agree a SoS is a highly complexity entity. However, complexity is a subjective term. When microcomputers were introduced back in the 1970s, they were considered to be complex machines, but those same machines are considered to be simple by today's standards. This is in part because the computer industry has developed technology, procedures and standard interfaces between components to handle the complexities. Systems of systems are considered complex today because reliable procedures and techniques to design and analyze them have not yet been developed. Indeed, researchers are currently expending much effort trying to work out the required procedures [3][4][5]. For entrepreneurs, inventors and engineers, this lack of structure equals room for innovation.

This paper looks at systems of systems through the lens of innovation theory. The next section gives a brief outline of some of the theories about innovation. These theories are then applied to a system of systems framework, with examples that could be applied to a classic system of systems – transportation systems [6].

II. Innovation Theories

Innovation has been called the engine that drives economic growth and this idea is the force behind research into the innovation process. The difficulty is that no one has yet come up with a reliable formula for creating breakthrough new products, services or processes. Therefore, a great deal of innovation research focuses on peripheral issues, such as what is the best government policy to promote innovation [7][8], or models of the innovation process [9]. In this paper,

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we are concerned with the question of where to look for opportunities for innovation and how to evaluate a potential innovation in the system of systems area.

A. *Who Can Innovate?*

There are two major sources of information that address the question of where innovations come from: psychological studies of people who have introduced paradigm-shifting advancements and business studies of where in the value chain new inventions come from. The value chain can be thought of as a model of how value is added to raw materials from material supplier to manufacturer to distributor to retailer to end user. Concepts from both psychology and business can be combined to predict where innovations in SoS are likely to come from.

Analysis of people who have introduced major innovations into the world have come up with a few guidelines as to what makes people creative [10][11]. First, there is an element of luck involved in being in the right place with the right skills at the right time. A nomadic San bushman living in Botswana may be highly intelligent, but he is unlikely to make any contribution to the field of avionics. Second, it is critically important for a person to be keenly interested in their field of choice. Indeed, noted inventors and scientists often express a feeling of beauty or joy associated with their chosen profession [11]. This love of their work allows them to put in long hours learning the accepted rules of their profession. Moreover, such people tend to develop an overall picture of their chosen field, being able to analyze it from multiple perspectives. This is a characteristic that favors systems engineers in developing innovative ideas. Third, a long apprenticeship (usually about ten years) in a field must take place before a major contribution can normally be made [12]. Fourth, highly inventive people have an innate sense of intuition about what will and will not work. This intuition is developed slowly, over a period of years, by working on a variety of loosely related problems that allows for a generalization of important concepts. Fifth, inventive people are very productive – they produce a lot of works. It is not that they are geniuses, because while they may produce many great works, they also produce a lot of mediocre ones. When asked how to come up with a good idea, chemist and Nobel Laureate Linus Pauling responded that the key was to come up with a lot of ideas and throw out the bad ones [10]. Finally, creative people tend to be well read and have a lot of different experiences. They tend to work in many different sides of an industry, rather than specializing in a narrow field. This broad background allows them to generalize about the entire field

At this point a natural question arises as to whether there is any way to speed up the innovation process. High achievement in individuals comes from a combination of above average skills, high motivation and creativity [13]. These characteristics can also be present in teams of people, with each member having a different set of strengths. One phenomenon in particular that fosters the spread of new ideas is the existence of weak social networks [14]. A strong social network exists when everyone in a group of people knows and interacts with all other members on a regular basis, such as a group of engineers all working in the avionics department of an airline. In strong social networks, people tend to think alike and solve problems in the same way. Social networks with weak ties occur when one member of a strong network interacts with one member of an unrelated strong network. This might be the case when one engineer from the avionics department befriends someone in the advertising department of an airline. There is strong evidence that new ideas flow along networks with weak ties. One successful strategy for innovation is to create "technology brokers", people who form weak social networks with outside groups and bring new ideas to solve problems [15]. In a SoS framework, a technology broker might be someone who has contacts with many potential subsystem groups, such as an airline engineer with contacts in trucking, cruise line and railroad industries.

Von Hippel conducted a ground-breaking study over a number of different industries of who in the value chain – users, suppliers, manufacturers, distributors or others - develops new products, services or processes [16]. The answer turned out that any one of these groups could introduce innovations, but that an invention usually came from the group or organization that benefited from it the most. Often, that benefit was in the form of money, but could also be in the form of increased capabilities or other non-monetary gains.

A few conclusions can be drawn from the above discussion. Innovation comes from people or groups who have worked in a field long enough to know the rules and have a broad knowledge of the entire field. They are highly productive in that they produce a lot of ideas and then experiment to determine the best ones. Ideas can also come from technology brokers who hold regular informal discussions with employees of different companies and outside groups. Moreover, new ideas are likely to be developed by groups that will benefit most from them. From a SoS standpoint, innovation is likely to come from a person or group that has good knowledge about the SoS component systems, has knowledge of how to put these component systems together in an overall SoS (or is willing to experiment with the SoS architecture) and is highly motivated by a vision of the potential gains or capabilities the SoS will provide.

III. Theories of Innovation for Commercial Success

Theory in the chaotic business world is not as precise as in the well-structured discipline of engineering, but innovation theory can still be a powerful tool to analyze the potential acceptance of a given invention [17]. The following section reviews some of the theories proposed to explain company success or failure and comments on their applicability to SoS problems.

In the 1970s, Abernathy and Utterback [18] proposed an influential model of innovation that included three stages, a fluid, transitional and specific phase. The fluid phase is a time of great uncertainty, when companies are experimenting, trying to find the right technology and market strategies. Once strategies are set, the transition stage begins, during which standards are developed to enhance productivity. In the specific phase, a dominant design emerges that kills off competing rivals.

One theme that occurs throughout innovation studies is the importance of experimentation in the early stages of an idea [19]. This is true for choosing both technologies and market strategies [20][21]. Crucial in this stage is being organized to rapidly conduct a series of experiments early in the process to find out what works and what doesn't. Especially important is avoiding commitment to one idea or design too soon, so that valuable resources are not long committed to dead end paths.

SoS engineering appears to be in the fluid phase right now, where experimentation is occurring to find the best design methodologies. Although there is a push to develop SoS standards, these may be premature. Interestingly, in the quest to develop SoS methodologies, iterative methods have been proposed as standards [3]. This seems to indicate the recognition of the necessity of experimentation in developing SoS.

Teece proposed a model to explain why some companies fail to profit from innovation [22]. This model posits that if a product or service is easy to imitate by other firms, then the complimentary assets of a company will determine who is best able to profit from it. Complimentary assets are the resources a company has to provide services such as marketing, manufacturing and after-sales support. Because SoS engineers design products using component systems that may be readily available to others, this theory has important implications for the field.

A. *Component versus Architecture Design*

Clark and Henderson [23] proposed a framework of innovation that is particularly relevant to SoS. This theory, based on empirical evidence from the semiconductor processing equipment industry, notes that systems innovation comes in two forms: ideas that improve the components in a system and ideas that change the way that components are put together to from a system (system architecture). Breakthrough or radically new products frequently use new architectures to provide new capabilities. However, once an architecture is set, it rarely changes. Improvements in the product function are obtained by improving the performance of the components that make up the product. Over time, architectural knowledge becomes embedded in a company's organization and procedures. Because this knowledge is now implicit, it is difficult for a company to change the architecture of its products.

According to the Clark and Henderson model, SoS engineers are perfectly poised to create breakthrough products and capabilities, since high level architecture design is the specialty of these engineers. On the other hand, improving a product once its overall architecture is set will prove difficult in a SoS framework, since engineers have no access to the component systems.

B. *Resources, Processes and Values*

Christensen [20][21] proposed a series of theories that have become widely accepted since they were first proposed starting in 1997. The Resources, Processes, Values (RPV) theory builds upon the work of Clark and Henderson, who noted that a company's structure and information-processing procedures are built around an established architecture [23]. RPV theory states that what a company can and cannot do is determined by their resources, processes and values. Resources – people, money, equipment, etc. – are easy to change. It is relatively easy to buy new equipment, retrain workers or hire new employees with desirable skills. Processes - the procedures a company uses to get things done – are much more difficult to change. Values – principles that determine how decisions are made – are the most difficult of all to change. As an example of company values, Southwest Airlines prides itself on being the low cost airline, while Singapore Airlines emphasizes service. To alleviate boredom on long flight, Singapore Airlines may put in entertainment centers in seats (high cost), while Southwest Airlines may have stewardesses tell stories to passengers (low cost). The important point here is that a company that values high profit margin customers and has procedures to support that value cannot attack low profit margin business opportunities because their procedures and decision-making processes does not allow them to do so.

C. *Disruptive versus Sustaining Innovation*

The idea of dividing innovations into radical or incremental categories has been around for a long time under various names (see [23], for example). Christensen [20] uses the terms disruptive and sustaining for these categories. Sustaining innovations are incremental improvements in what is already being sold, and are best developed by established firms in a market. This type of invention is relatively easy to develop and implement. They key is to observe what a company's customers do with a product and ask how they will evaluate any new feature [24]. People purchase products to do a job and sustaining innovations should help them accomplish important tasks either better or more efficiently. Because sustaining innovations are sold to existing customers using existing distribution channels, they are relatively low risk. Existing companies have a huge advantage over new entrants in developing and selling sustaining innovations because they already have the processes, values and relationships with customers that make them efficient at it. Sustaining inventions are geared towards undershot customers – customers who demand better performance and are willing to pay for it. These are the high profit margin clients that many companies value the most.

The chances of a new company succeeding in an established market, selling to the existing customers of an established firm are quite low [21][25][26][27]. This is because an existing company has the resources, motivation and processes to meet any challenges in its existing businesses. The best chance for a new company to succeed in the marketplace is to develop a disruptive innovation that uses existing technology to address a new need – new customers with new distribution channels. With a disruptive strategy, the chances for a startup company to succeed improve six fold.

Disruptive Innovations are those that have no existing markets. Companies must sell their products or services to non-consumers - *people who do not currently use a product* *or service because it is to costly, they do not have the skill to use it or the do not have access to it* - or overshot customers - *customers who currently use a product that has capabilities beyond what they need and therefore could be lured away by a product that is simpler or cheaper, but still meets their needs*. Disruptive technologies tend to be cheap and low performing compared to mainstream products, but they can succeed in the marketplace because they are attractive to a certain segment of the population that does not require high performance. New companies with disruptive technology that are trying to create a new market do not have a lot of time to succeed. Research shows that these companies must rapidly experiment to find a profitable strategy in order to survive.

Existing firms often do not see new companies selling disruptive innovations as a threat, because they sell into low profit margin markets using new distribution channels. However, disruptive innovations tend to improve faster than customer's needs do. Eventually, a disruptive company's products can meet the needs of the most demanding customers. When this happens, disruptive companies can drive incumbents out of business because the cost structure of the disruptive firm is lower than the formerly dominant firms.

An important step in introducing disruptive innovations may be finding a visionary with deep pockets to support it [25]. Disruptive products, especially if they employ new technology, are often rough, relatively poor performing and difficult to use. Visionaries don't mind this, because they see a potential application that is so compelling that the problems pail in comparison with the potential benefit of a market changing disruption.

Within a SoS framework, we can think of the owners of the component systems as being incumbent firms looking to maintain their product or create sustaining innovations. SoS design is difficult, with the designer having to integrate many independent entities and being subject to unexpected change at any time in the component systems. Therefore, the SoS designer is likely to be a visionary, looking for breakthrough capabilities or trying to solve pressing problems that have no easy solution. As such, SoS designs have the capability to be disruptive in the marketplace. Ironically, this implies that as the SoS improves, it may have the capability of putting one or more of its component system owners out of business.

D. Value Chain Evolution Theory

The final piece of Christensen's theory involves categorizing companies according to their degree of integration. Fully integrated companies execute all activities in producing a product or service themselves. This strategy is common when the performance of product not good enough to meet customers needs. For example, supercomputer manufacturers tend to be integrated because they are trying to squeeze every last ounce of performance out of their machines.

On the other end of the scale, companies can specialize in one component of a product or one particular area of a problem and choose partners to put together a total solution. This is the solution we now see in the microcomputer industry - companies specialize on monitors, hard drives, memory, graphics cards, etc. Standards are used to interface between components, allowing for modular designs. Companies need to determine how they can provide the most value and follow that path.

The best strategy in terms of integration versus specialization for a company depends on the state of customer satisfaction with their product. The criteria by which customers choose products are (in order of importance): 1) functionality; 2) reliability; 3) ease of use; 4) customization; and 5) price. When a product is functional enough to meet a user's needs, they then look for reliable products; when a product is functional and reliable enough for a customer, they then choose products that are easy to use.

Companies with disruptive innovations need to quickly find a niche market with a pressing problem they can solve [25]. As the product improves and becomes more reliable, these companies need to start partnering with other firms to provide an easy to use total solution in larger markets. SoS are interesting because there is usually a pressing problem, otherwise there would be no need for a SoS. The usual solution to critical problems (where performance is paramount) is integration of all components. However, with SoS, integration may not be an option because of regulation, lack of expertise or lack of resources. Therefore SoS combines services provided by others, a strategy normally reserved for when available performance greatly exceeds needs, to solve a problem where performance is crucial.

IV. SoS Example – Air Transportation

A commonly used example of a SoS is transportation systems, which include all modes of moving people and cargo: cars, trucks ships, trains, airplanes, etc [1]. Because each of these modes is controlled by a different regulatory agency and the procedures for doing business are different across them, these count as a SoS. It is important to note that the component systems are not completely independent from each other, but have a degree of cooperation in order to make the whole system run smoother. For example, an airport will have car rental kiosks in its terminals, linking the air and ground transportation systems together.

DeLarentis proposed air transportation as an example SoS, with a suggestion for an air taxi system that uses local airports not normally used for commercial transportation by the major airlines [6]. In this case, the air taxi would be one component system in the overall air transportation SoS. I would like to examine this option as an example to see how innovation theory fits in a SoS framework.

The problem presented is this: getting from one small, isolated town (let's say Mena, Arkansas) to another in a different state (Beeville, Texas, for example) for a weekend visit or two day business trip. The towns are far enough apart that driving would be difficult for such a short trip. Taking a bus is inconvenient – travelers must change busses midway and take a long time to get there. The only practical option is to take an airplane, but even this is complicated. To use a commercial airline, one must drive from Mena to Little Rock, park in the airport, take a plane to Dallas, change planes to San Antonio, rent a car at the San Antonio airport and then drive to Beeville. The entire process can take eight or more hours one way and have considerable expense involved with gasoline, parking, airfare and car rental. As a leisure traveler going to visit my cousin, I am not willing to put up with the time and expense involved and so am a non-consumer of this service. If I do occasionally take the trip, I will book my ticket well in advance and buy the cheapest fare available. In other words, I would be a low profit margin customer for the major airlines.

If I have a business in Mena and a branch in Beeville, I may have no choice but to make the trip. In fact, I may need to often make the trip for business reasons. In this case, I am an undershot customer, because I am using the service, but would like better performance (shorter trip length). When I fly, I may need to go on short notice and may wish to fly first class to make the long trip more agreeable. In this case, I am a high profit margin customer for the airline.

A. Air Taxi as System Component

A possible solution to the problem of traveling between the two towns is to open an air taxi service that flies from the local airport in Mena to the local airport in Beeville on demand. Is this a viable business and can it disrupt existing air service? Let's assume that on every trip there are enough travelers to fill a small plane and that the plane can fly non-stop from Mena to Beeville. Let's further assume that there are no regulatory issues that would prevent an air taxi service from operating. For simplicity, only two towns are used in this example, although a viable business would need to operate between several such towns.

For the leisure traveler, this service provides an opportunity to travel that did not exist before – access to a weekend trip. Such a service can convert a non-user into a customer, even if the costs are higher than using the commercial airline out of Little Rock. Currently, charter service would cost about twice as much per person as would using a regularly scheduled commercial flight and renting a car. As time goes on and more people use the service, it is likely to become cheaper, more reliable and easier to use. This business model can succeed (provided enough people want the service) because it does not compete directly with commercial airlines.

Now lets examine the business traveler, who is more concerned with time and service than costs. In fact, the costs in using an air taxi and first class travel on the commercial airline will not be that different. However, the traveler will be delighted with the time saved by the air taxi service, but may still like better service in order to save time.

What will be the response from commercial airlines? In this case, the taxi service is going after the airlines best, highest profit margin customer. If enough people switch from commercial, first class airlines to air taxis, the commercial airline will have no choice but to respond. According to the Teece model, an air taxi service (as described above) can be easily imitated. Moreover, the airlines have far greater resources (complimentary assets) than a startup company does. This bodes well for commercial airlines. We also need to look at the architecture of the service. DeLarentis examined a central hub system for air taxis, much like what major airlines use at main airports. If the structure of an air taxi service is similar to what the major airlines now use, but on a smaller scale, then the airlines can use their existing procedures to compete for this business. Moreover, because their survival depends on keeping their best customers, history predicts that the commercial airlines will win the battle. On the other hand, if an air taxi service is structured to be a point-to-point service, similar to what land taxis structure is, then the small air taxi services should be able to successfully compete with major airlines.

B. Air Taxi SoS

The above analysis looks at an air taxi as an isolated system in an overall "air transportation SoS". However, air travel is just one component of an overall trip from Mena to Beeville. A traveler still needs to get from their house to the local airport, perhaps find secure parking at or near the airport and, once in Beeville, get from the local airport to their destination. If someone is a leisure traveler, they can cobble together solutions to these problems and still be happy, because the air taxi allows them to do something they could not before: travel to Beeville for a weekend. For the business traveler, however, these inconveniences could be a major impediment to acceptance of this service. In this situation, there are two possible solutions: design an "air-land taxi SoS" or build a totally integrated land-air transportation system solution.

The fully integrated solution has the potential to deliver the best customer experience. For example, the air taxi service can provide a limousine to pick the customer up at their house or business and drive them to the airport. Once at the destination, the taxi service can provide a car for the customer or limousine drop off service at a home or business. This type of service is difficult to set up because of the cost, time involved and regulatory issues. The costs will be especially prohibitive if several local airports are used. However, once set up, an integrated solution is hard for new entrants to compete with.

The alternative is to set up a true SoS by using existing taxi or limousine services in Mena and Beeville, existing secure parking facilities near the local airports, existing reservation services and perhaps systems to notify customers of delays and weather problems. As time goes on and business improves, more taxi services may become available and pickup and departure times can become standardized. This scenario leads to a modularized design, where one can pick and choose transportation services (usually on the basis of cost or convenience). However, if business is good, it will be easy for another company to provide the same service.

V. Conclusions

Innovation in a SoS context provides an interesting challenge, because SoS defy the normal rules of innovation. SoS design is often required when a complex problem arises, requiring a complex solution. When a pressing problem occurs that requires high performance, normally full integration of a product or service in a single company is the response. In SoS, the response is to use products or services outside the designer's control – normally a strategy for when performance is good enough for customer's needs.

By its nature, SoS design allows for breakthrough products and services to be introduced. However, because SoS designers do not control their component systems, it is difficult to make the incremental improvements that normally occur over a product's lifetime. Moreover, because SoS use readily available components, it is easy for products with similar performance to be introduced by other companies.

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