A SoS Perspective of Critical Infrastructure Systems Development

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ABSTRACT:
Critical infrastructural systems are complex systems of systems (SoS). Taking a SoS perspective of large-scale infrastructural development can be beneficial in better understanding the inherent problems of emergent complexity. SoS is a relatively new term that is being applied primarily to addressing large scale inter-disciplinary developmental challenges with multiple, heterogeneous, and distributed network-centric systems. A large-scale infrastructural system can be hierarchically structured from its building blocks to higher multi-levels of network. An infrastructural SoS is usually developed in evolutionary stages integrating existing systems with upgraded or extended systems. Complex infrastructural systems are non-monolithic and they share certain common characteristics which can be developed into a set of discriminators to develop a framework for SoS engineering management addressing issues in an evolutionary planning and staged development, stakeholder management and leadership for complex systems integration. The framework is then used to compare with and appreciate the observed characteristics of real-world major infrastructural development using Singapore-based case examples.

Keywords: Critical Infrastructural development, Complexity, Complex systems, System of systems (SoS), Singapore cases

INTRODUCTION

For sustainable economic development, governments must continually fund and develop large infrastructural projects. The challenge is to build these infrastructural developmental projects in an ever shorter timeframe and in the most cost effective manner to cope with increasing demand for providing critical public services in support of societal and economic activities.

The objective of this paper is to go beyond the traditional project, program and portfolio management perspective to explore other alternative views and understanding when dealing with complex large-scale systems development. A special interest is to explore the integration of existing or legacy systems with new or extended component systems into a network-centric distributed system of systems (SoS). The SoS idea is not about a collection of isolated stand-alone systems in a project portfolio. SoS is dealing with the building of interoperable multiple projects into a network-like living system in evolutionary stages over a longer period of time especially in the case infrastructural development.

The main focus of this paper is to review relevant and commonly cited reference on the definition of SoS and to indentify and synthesize a set of characteristics which may be used to develop a set of SoS discriminators provide guidance for managing project complexity. Case examples from Singapore's national transportation systems of systems will be used to illustrate a fresh perspective of a system of systems architecture which would be both multilayered and distributed.

Study on SoS and SoSE

System of Systems (SoS) is a relatively new term that is being applied and promoted primarily by the defense establishments. The study of System of Systems (SoS) and the System of Systems Engineering (SoSE) as an enabling process is yet to be established as a mature discipline and adopted in complex project management study. This paper attempts to explore and extend existing work done by SoS researchers and government agencies, mainly in the US, and gain a greater appreciation of the characteristics of SoS and its implication and benefits by planners and architects when working on evolving infrastructural projects.

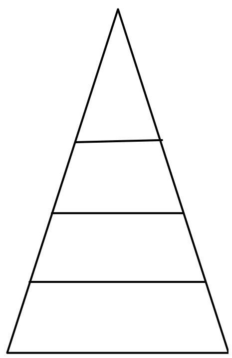
The paper makes a proposition that a broadly defined SoS master plan and architecture should be, as far as possible, formulated from the early phases of the project development where the level of influence over future developments is the greatest. The staged development is particularly valuable which allows incremental learning, building of capability maturity in systems engineering process, and a more strategic risk management approach. A long term strategic and dynamic perspective of SoS development is critically important due to the high level of investment required and its impact on other interoperable and interdependent systems.

An evolutionary SoS development also requires continual rejuvenation, improvement and innovation to the existing or extended systems due to learning and introduction of new processes, products or technological components.

A Hierarchy of SoS

There is still not a single universally accepted definition of SoS and a definitive implication which remains elusive. However, there is no lack of previous attempts trying to define it. To better understand the concepts of SoS and its implications in future systems planning, design and application, a review of some of the more commonly cited definitions would be useful and provide a good start in the study.

A complex system can be both a SoS on its own or a component system for another SoS. Taking a global view, there is likely a hierarchy of system of systems. For instance, a Global Positioning System (GPS) is a SoS on its own and a component system of the global communication system. A mass rapid transit system can be a SoS on its own and an integral component of a broader land transport system. Figure 1 illustrates a hierarchy of systems for a national land transport system. This hierarchy of SoS can be defined at the higher beta-gamma-delta levels when component systems are organized in a network. It is expected that the characteristics of SoS is getting stronger and more prominent at the higher levels of the hierarchy. At the last or base level of the hierarchy is represented by all the necessary building blocks or entities that contribute to the next higher level systems. The alpha-level is in the realm of systems engineering of component single systems. The four-level hierarchy is only indicative as the number of levels will be increased for a larger system. For instance, a national transport system of systems can be defined at the epsilon (ε) level that comprises land, air and sea transport systems which are organized as delta-level networks.



Delta (δ): Collections of δ-level systems, organized in a network e.g. National land transport network

Gamma (γ): Collections of γ-level systems, organized in a network e.g. Nation- wide Rail network

Beta (β): Collections of β-level systems, organized in a network e.g. MRT lines

Alpha (α): Base level of entities or system building blocks e.g. MRT stations

Figure 1: Hierarchy of National Land Transportation System of Systems (adapted from DeLaurentis and Callaway (2004)

The SoS and SoS Engineering (SoSE) process have in recent years been explored as a useful perspective and a way to represent and describe a strategic and holistic economic and operational approach to enhancing or extending existing system capabilities. SoSE may be perceived as a special class of large scale systems engineering (SE) that enables the SoS deliveries. Development of SoS and SoSE as a viable discipline is still work in progress.

Characteristics of SoS

The definition of what a SoS is varied. The variation depends on the type and application domain of the systems. In the business domain, a SoS is about the enterprise-wide integration and sharing of core business information across functional and geographical areas. A large global enterprise information system like ERP II or Internet-ERP can be considered as a SoS. In the military domain, a SoS is a communications infrastructure and a configurable set of component systems to support military operations in a constantly changing dynamic environment.

Manthrope's (1996) military-specific definition states in relation to joint war-fighting that SoS is concerned with interoperability and synergism of Command, Control, Computers, Communications and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR).

An SoS may also be a multisystem architecture that is planned up-front by a prime contractor or lead system integrator or government agencies such as in the cases of a nation-wide defense system, aviation and airport system, or land transport system. For instance a land transport system incorporate multiple systems in mass rapid transit rail network system, a network of expressways, an electronic road pricing (ERP) system, and even a private car ownership bidding system as in the case of Singapore.

In other cases, a SoS can be an ad hoc architecture that evolves serendipitously over time, often configured or reconfigured in incremental improvements in response to organizational needs, new market demands, new technologies and innovations, and available funding. The ad hoc evolutionary SoS architecture tends to be a network-centric architecture that grows with needs and available resources.

Defining what constitute a definitive SoS remains a challenge, depending on an individual system observer's system-of-interest perspective. The other challenge is what benefits will a better understanding of SoS characteristics bring to the systems architects, planners, implementers and operators.

Further References of SoS Characteristics

The followings are some commonly cited SoS definitions that may be relevant and useful to extract criteria for conforming certain major infrastructural projects as SoSs. References on SoS definition are mainly taken from Lane and Valerdi (2007).

1) SoS are large *geographically distributed assemblages* developed using *centrally directed development efforts* in which the component systems and their integration are *deliberately, and centrally, planned* for a particular *purpose* (Eisner 1993). This definition is useful to describe many government funded infrastructural projects such as national transport systems, where relevant government agencies and their dedicated project teams are responsible for master planning, design, and contract awards and administration over the prime contractors and specialist venders. Example of a mass rapid transit system is dimensionally large and geographically distributed systems.

2) SoS is non-monolithic and has proposed five distinguishing characteristics (Maier 1998). These characteristics are: i) *operational independence* and ii) *managerial independence* of the component systems, iii) *evolutionary development*, iv) *emergent behavior* & v) *geographical distribution*.

These five defining characteristics are very useful as they rather accurately describe the many critical infrastructural developments including a network of land transport systems. In the case of Singapore both its expressway and MRT network systems have been developed in several stages in decades mainly driven by the needs to satisfy increasing demands of passengers and users due to growing population, economy and social activities in a compact urban city. Operational and managerial independence are likely to achieve at the higher delta (δ) or even epsilon (ε) levels.

There are accompanied emergences as the infrastructural systems continual to evolve as new developments or extensions are added. For examples, valuable real-estates such as shopping malls and condominium are built by or around the MRT stations radically affecting the ways people live. The MRT line has also been extended to the international airport to improve connectivity for both international and domestic travelers.

There are variants in defining SoS characteristics. Boardman and Sauser (2006) define five distinguishing SoS characteristics similar to Maier's in operational and managerial independence (autonomy) and emergence, but differentiate by adding characteristics in belonging, connectivity and diversity:

i) Autonomy: Constituent (versus component) systems enjoy managerial and operational independence while accomplishing the purpose of SoS.
ii) Belonging: Constituent systems have the right and ability to choose to belong to SoS.
iii) Connectivity: The ability to stay connected to other constituent systems.
iv) Diversity: Evidence of visible heterogeneity.
Emergence: Formation of new properties as a result of developmental or evolutionary process.

Diversity refers to the non-monolithic characteristics together with *connectivity* are not particularly unique in describing a SoS, but can be taken as given for any complex systems including SoS. If *Belonging* refers to the freedom to choose to belong, it will mostly like fail to describe a critical infrastructure system. If we define Belonging as a sense of shared mission and belonging by the constituent systems, then it will make more sense in achieving better interoperability among the autonomous constituent systems. The *autonomy* does not grant full independence to the constituent systems which would be governed or regulated through a set of high-level protocols. A well formulated set of protocols are like to enable positive emergence with desirable outcomes.

3) SoS is an *evolving mix of legacy and new system:* especially an information-intensive domain. Such description is a useful and valid discriminator for critical infrastructure development. Developing a SoS, especially one involving a number of legacy systems is a far more complex project than developing a stand-alone green-field system, even it is a very complex one. The prioritized requirement to integrate and seamlessly interface existing and new component systems and to ensure smooth interoperability with low risk start-up and early achievement of acceptable performance level can be a very challenging complex SoSE process (Carlock and Fenton 2001).

4) A system will be called a SoS when all or a majority of the five characteristics defined by Maier (1998) are present according to Sage and Cuppan (2001).

5) SoS *leadership:* as required in the role of *Lead System Integrators* (LSIs) is not limited to internal capabilities in systems engineering and design, which are not enough. They must be also visionaries and leaders who can coordinate, motivate, direct and work closely with a set of stakeholders such as prime contractors, key suppliers and government agencies, and in making strategic institutional arrangements (Gupta 2003).

An LSI is agent with the authority to plan, acquire and integrate assets from a variety of potential system suppliers on behalf of an owner organization or a government agency that is acquiring or implementing a complex infrastructural system. The LSI has the authority to contract with and manage other suppliers on behalf of the acquiring authorities. These leadership requirements should be taken as given and not unique. Great emphasis should be given to the cultivation and development such leadership for complex system planning and management.

6) SoS as a *meta-system* (Keating et al 2003): comprised of *multiple* embedded and *interrelated autonomous complex subsystems* that can be *diverse* in technology, context, operation, geography, and conceptual frame. These complex subsystems must function as an integrated meta-system to produce desirable results in performance to achieve a higher-level mission subject to constraints.

7) The SoS is *reconfigurable* and has evolutionary properties: as stated in United States Air Force Scientific Advisory Board (USAF SAB 2005) guide. In SoS re-configuration, component systems can be added/removed during use; each provides useful services in its own right and each is managed for those services. Yet, together they exhibit a synergistic, transcendent capability.

These specific properties are more relevant to mobile and flexible nodes in a distributed network, as the nodes and links can be easily removed or added as required. For infrastructural SoS, the component systems tend to be more fixed that are not easily removable or reconfigurable. However, these infrastructural systems like the airport terminals are continually renovated or reconfigured to incorporate new features for safety, security and streamlining of operations. These periodic renovations are rejuvenation to the existing and probably aging legacy systems by injecting new energy and vitality. Reconfiguration is also needed when new facilities or improved technologies are available or incorporated into the new or extended component systems. For example, when Terminal 3 of the Changi airport is built, the destination-tagged automated baggage handling system (BHS) (at α-level) has to be integrated with the existing counterpart systems in Terminal T2 and T1. It is also likely the legacy systems in the older terminals have to be upgraded to ensure compatibility and interfaces.

A FRAMEWORK FOR SOSE MANAGEMENT

Related to the above characterization, SoSE is thus defined as: the process of planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into an (emergent) SoS capability that is greater than the sum of the capabilities of the constituent parts. This process emphasizes the process of discovering, developing, and implementing standards that promote interoperability among systems developed via different sponsorship, management, and primary acquisition processes (USAF SAB 2005).

The most popular characteristics used across the above definitions are adapted as follow:

"Emergent behavior", "Concurrent", "Synergistic", "higher level purpose", "Complex", "dimensionally large, geographically spread/distributed", "Interoperable systems", "Centrally directed, relative independence at both operational and managerial levels", "Mix of existing, new or diverse systems" , "Evolutionary/ staged development", "strategic investment analysis"..

These characteristics can be further synthesized into a Process-Organization/People-Product/System framework as shown in Figure 2. The framework represents a large-scale SoS change management which can also be further developed for SoS engineering management.

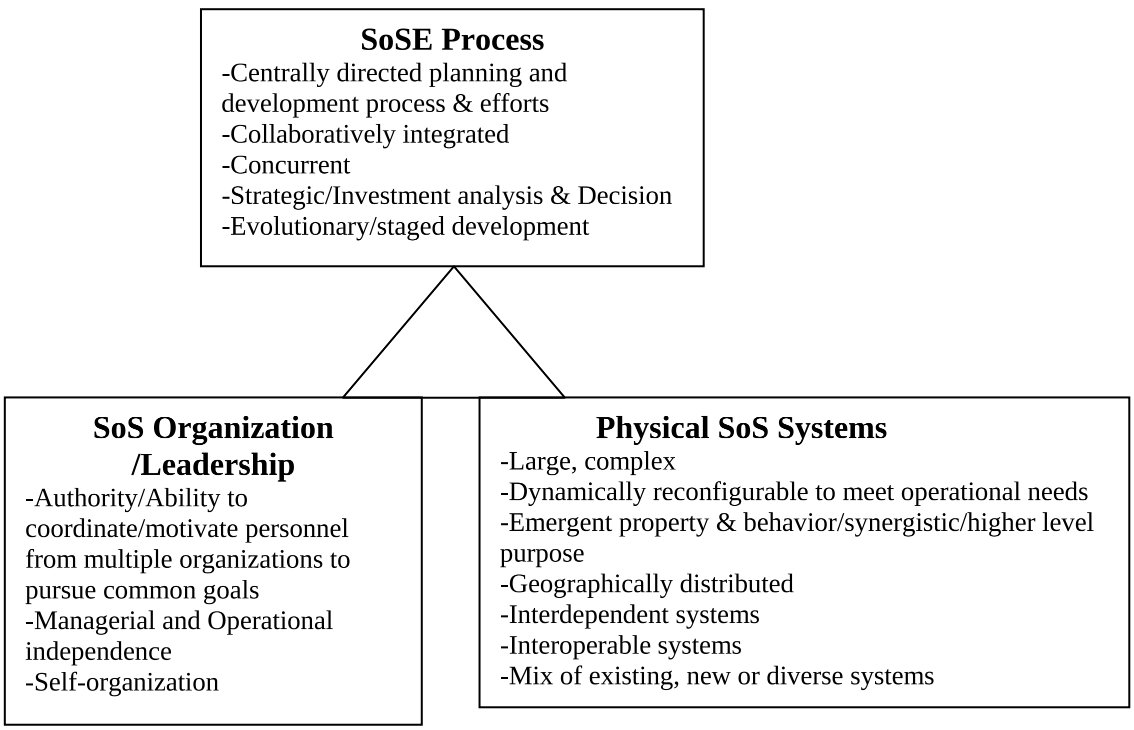


Figure 2: A framework on SoS Engineering Management

Discriminators for SoS Engineering Management

Lane and Valerdi (2007) use discriminators to filter out SoSs that conform to certain criteria. The following discriminators are adapted which can be used to delineate the process, organizational and physical system aspects of SoSE management.

1) *Economically-oriented SoS stakeholders:* There exist strategically-oriented organizations including: *Clients* (developer and government agencies/authorities) that will pay for building the systems, *operators* (responsible for the operation and sustainment of the built systems) who will receive revenues from *user communities* who use the operated systems.

2) *SoSE Responsibilities and Processes:* The SoSE process is centrally directed planning and development process. It is collaboratively integrated, often with prior institutional arrangements. The Lead System Integrator (LSI)(s) is responsible for the definition of the overall SoS architecture, and the total component systems integration, testing and commission activities at the SoS level.

The process is "concurrent" which takes a SoS life cycle view considering future requirements, as needs for future rejuvenation and extension or expansion. The SoSE and architecting processes should be strategic in nature involving investment analysis & long term decisions. The SoSE is likely to be evolutionary involving staged development as a living system. The SoS infrastructural development will be human-centered, perceived as a human activity system (HAS).

Leadership Responsibility: The SoS program must be led by a single or a set of lead systems integrator (LSI)(s) who could be prime contractor, system architect/planner, and/or government agencies vested with authority and accountability. With authority and resources, the LSI must have the commitment and ability to coordinate, motivate and direct component projects and operational personnel from multiple organizations, internal and external, to pursue common goals and shared mission. Managerial and operational independence and self-organization are expected at the component system levels subject to overall coordination by the LSI.

The LSI organization must also have complete technical oversight over the entire SoS and SoS component suppliers, as well as the engineering processes at the SoS level. The LSI is also responsible for defining an overall architectural vision for the SoS while maintaining the architectural concepts and integrity throughout the development, integration, and test phases (Lane and Valerdi, 2007).

3) *Component System-based SoS Architecture:* SoSE is primarily the process of integrating a set of component systems that work together (interoperable) to provide emergent behaviors (properties) not provided by any single component system within the architecture. The architecture design feature in a SoS provides the framework that supports the integration of existing as well as new component systems. The characteristics of this architecture determine

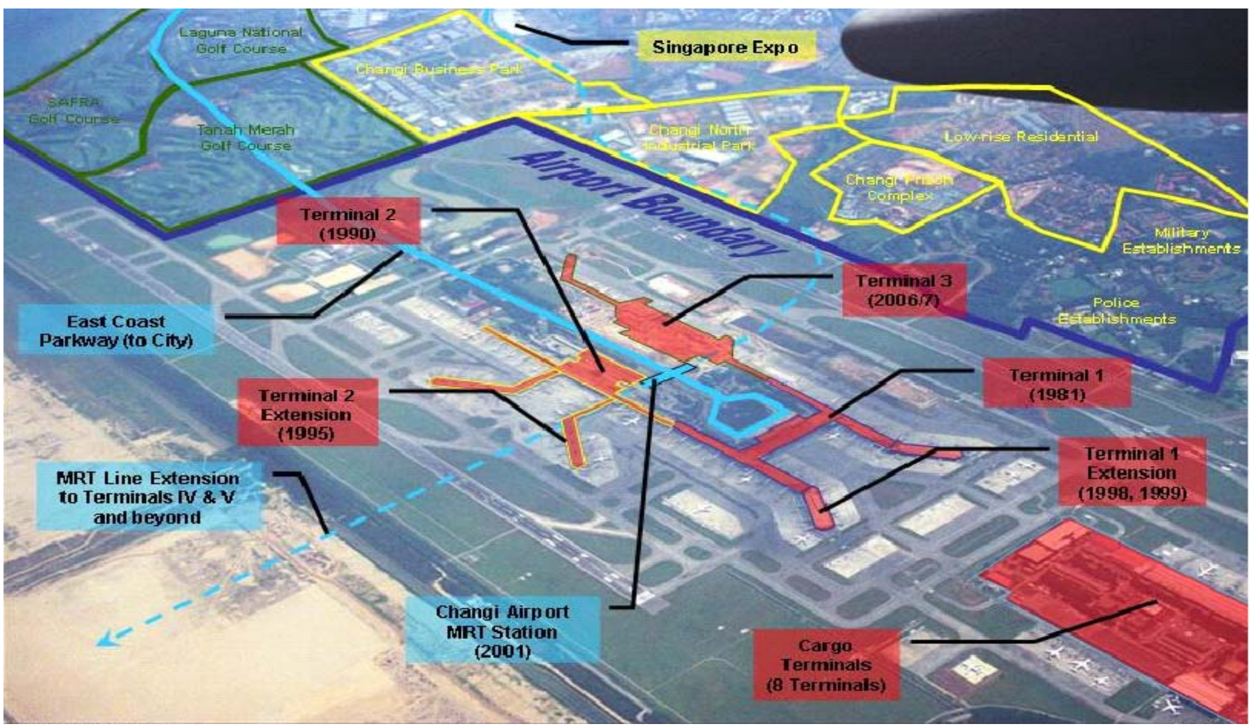
the ease/difficulty or implement-ability in integrating SoS component systems in both initial development and adapting to dynamic operational scenarios.

4) *Component systems Independence:* Each of the component systems envisioned within the SoS architecture must be independent with respect to management, development, maintenance, and operation. This provides for clear boundaries for responsibilities and accountability.

TESTING CONFORMANCE

To test the conformance against these discriminators for SoS engineering management, two major infrastructural systems are used as case examples. As stated earlier, the aim of the paper is to use Singapore's experience in the past decades in her rapid infrastructural development to examine and validate the relevance and benefits of a SoS perspective.

Case 1: Changi International Airport Complex (as illustrated below):



Changi airport has won the 'Best International Airport' title for the tenth year in 2007. The scale of operations is global with links to 189 cities in 60 countries. Currently there are 82 airlines operate over 4300 flights per week in & out of Singapore. In 2006, it handled 35 million passenger movements and more than 1.9 million tonnes of airfreight. Upon completion of Terminal 3 the total built capacities are now 70 million passenger movements and 2.5 million tonne cargo capacity per annum. The airport is now a premier integrated logistics hub in Asia and a comprehensive aerospace services hub in MRO (maintenance, repair & overhaul) in Asia

Pacific. The overall airport operation is managed by the Civil Aviation Authority of Singapore (CAAS) which acts as the overall LSI.

The development of Changi International Airport begun in 1975 and has gone through a complex evolutionary and growth process. In 1975 the Singapore government made a major decision to shift the then international airport from Paya Lebar, a former military airbase, to Changi, preparing for the arrival of Jumbo jets. The development is triggered and driven by an external technology driven event. After that the airport has undergone a staged development of the terminals. After Terminal 1 was built in 1981, Terminal 2 was launched in 1990, and Terminal 3 was ready in January 2008. Currently, the design of Terminal 4 has commenced in 2008.

The International Airport is a government-funded public infrastructural project and its continual growth is correlated to the economic growth and the expansion of business travels and tourism. Terminal T1, T2, and T3 have been developed as autonomous independent constituent systems over three decades to the still evolving Airport Complex (an Aeropolis) under an overall architecture as shown in the above illustration. The staged development can be conceptualized as a large-scale complex human-centered living system and has been continually rejuvenated periodically with upgrading and renovation to inject energy In order to meet rising passenger traffic volume and demands for high quality service level. A distributed staged development guided by an overall architecture and an evolving system design “protocols” such as expandability, aggregation and integration of new and legacy systems, ease of human-living/movement, visualization, green-design with natural lighting and energy conservation..

The airport can therefore be perceived as a human-centered living SoS capable on continual evolutionary growth. The study is motivated to find out whether the complex infrastructure development conforms to a set of SoS discriminators and a SoSE *process*.

The airport complex exhibits a hierarchy of SoSs similar to alpha-delta layers illustrated in Figure 1. At the terminal level there is connectivity at the base component level. For example, the automated baggage handling systems (BHS) represent a alpha-level entity which were interconnected and interoperable between the three terminals via an advanced software system.

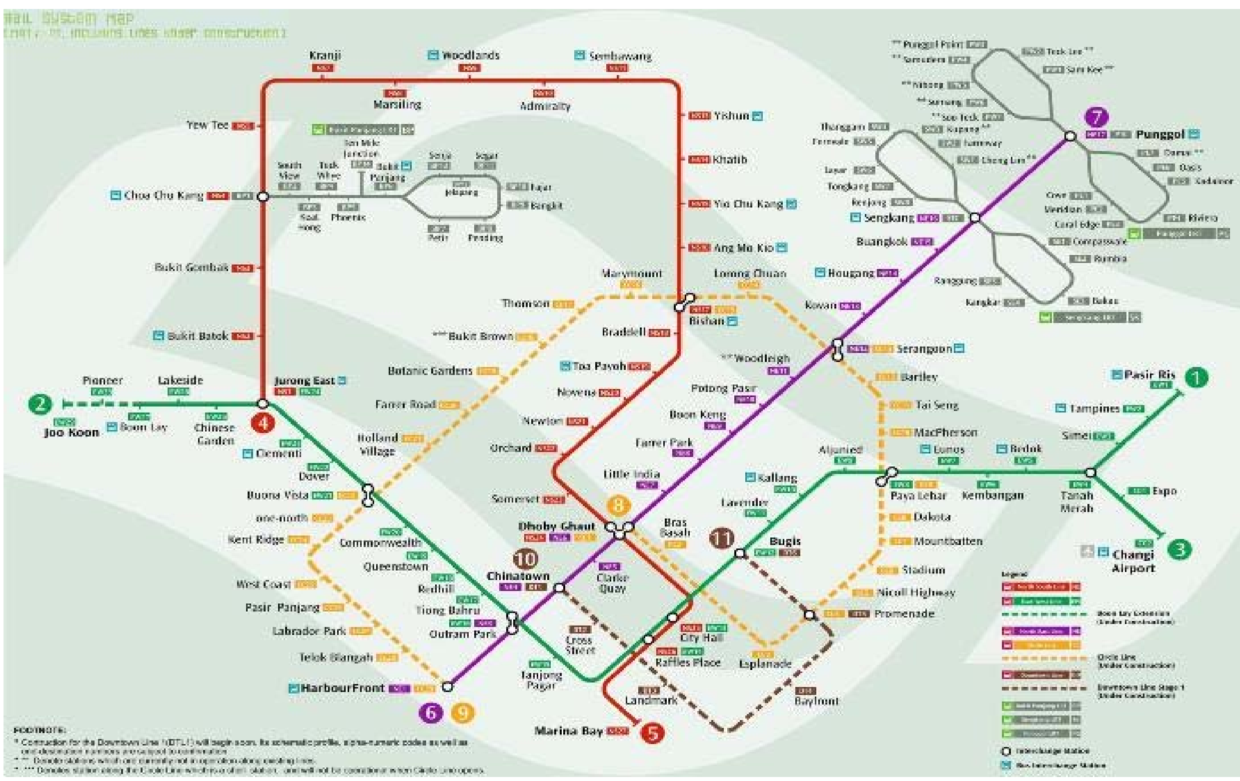
Table 1: Conformance of Changi International Airport with SoS Discriminators

Discriminator	Conformance
1.Economically-oriented SoS stakeholder	SoS owners: Civil Aviation Authority of Singapore (CAAS), authorized by Singapore Government: Ministry of Transportation. Singapore government funded the development. CAAS acts as the overall operator. The user communities are the various venders and air travelers who pay for the usage of the airport facilities.
2.SoSE Leadership Responsibilities and	LSI: CAAS centrally directs the planning, architecting, development and testing processes collaboratively with the airport

Processes	division of the former Public Work Department and the prime contractors.
3.Component system-based SoS Architecture	Integrate incrementally stage-by-stage development of airport terminals into an interoperable whole with evolving emergent behavior in enhanced performance and service level. The development process is evolutionary yet according to an overall architecture in support of the upgrading and integration of existing and new systems.
4.Component System Independence	Individual terminals can be operated independently with respect to development, maintenance and operations, though they share common facilities such as runways and air traffic control tower which are centrally coordinated.

Case 2: The Mass Rapid Transit (MRT) System (as illustrated below):

The rapid mass transit (MRT) system network illustrated below has been developed in stages incrementally since the early 1980s, to meet the growing land transport demands. It has co-evolved with other public and private transport component systems. It exhibits the evolutionary and expansionary development characteristics of a SoS.



From the above illustration, the Singapore MRT system has to-date four main lines namely, the North-South Line, East-West Line, North-East Line, and Circle Line. The Circle line will be operational in 2010. Interconnected with the main MRT lines are three Light Rail Transit (LRT) Systems in Bukit Panjang, Sengkang, and Ponggol serving three new satellite towns. Other interoperable land transport component systems are public bus systems, private busing systems, and taxis systems. There are other supporting systems such as the Electronic Road Pricing (ERP) System which is used to regulate the flow of traffic in the heavily used sections of the road network leading to the congested central business district (CBD) areas, by dynamically adjusting the road use charges on real time basis. The other well known policy-based regulatory system is the Vehicle Quota System (VQS) which uses a Certificate of Entitlement (COE) car Bidding System to control the supply of new private vehicles into the road network.

Table 2: Conformance of MRT (Land Transport) System with SoS Discriminators

Discriminator	Conformance
1.Economically-oriented SoS stakeholder	SoS owners: Land Transport Authority (LTA) of Singapore authorized by Singapore Government: Ministry of Transportation. Singapore government funded the development. LTA acts as an overall regulator and system architect. It assumed the initial operatorship of the initial phases of the MRT system which was then awarded to commercial operators for the various main lines. The user communities are the various venders and public commuting communities, who pay for the usage of the MRT facilities.
2.SoSE Leadership Responsibilities and Processes	LSI: Land Transport Authority (LTA) centrally directs the planning, systems development and testing processes collaboratively with the helps from international consultants and operators.
3.Component System-based SoS Architecture	Integrate incrementally stage-by-stage MRT system development interoperable with other land transport systems. The development process is evolutionary and according to an overall land transport system architecture and rising commuter demands.
4.Component System Independence	Individual MRT lines can be operated and managed independently on a commercial basis with profit and loss accountability. Each of the component systems are envisioned within a system of systems (SoS) architecture with clear boundaries for responsibilities and accountability, operational and financial.

CONCLUSIONS

This paper represents a preliminary attempt to gain a better understanding and appreciation of the notion of system of systems (SoS) through a set of commonly cited SoS characteristics, and the process of SoS Engineering (SoSE). Having identified and tested a set of SoS discriminators and their applicability for the planning, architecting and implementation of large scale complex infrastructural development systems, the next challenge is on how to further define and implement the SoS engineering management processes. The SoSE processes should consider a dynamic evolutionary staged development process with involving systemic learning and growing process capability maturity in design, operation and management of built system of systems. The SoS planner and program manager should take a fresh perspective that SoS has much larger scope and greater complexity of integration efforts between existing and new systems. The emphasis will be on flexible architecting with continuing architectural reconfiguration and design optimization. Continual modeling and simulation of emergent system of systems behavior will be necessary.

REFERENCES

J. Boardman, B. Sauser, Systems Thinking, CRC Press, 2008. 154-166.

P. Carlock and R. Fenton, System of systems (SoS) enterprise systems for information-intensive organizations, Systems Engineering 4(4), 2001, 242-261.

D. DeLaurentis, R Callaway, A System-of-Systems Perspective for Public Policy Decisions, Review for Policy Research 4th quarter edition 2004.

E, Eisner, Rapid computer-aided systems of systems engineering, Proc 3rd Int Symp Natl Council, Sys. Eng, 1993, Vol 1, 267-273.

C. Keating, et al, System of systems engineering, Eng Management Journal, 15(3), Sept. 2003, 36-25.

A. Gupta, Role and importance of lead system integrator in context of new air operations centers, MIT Sloan School of Management, Cambridge, MA, 2003.

J. A. Lane and R. Valerdi, Synthesizing SoS Concepts for use in Cost Modeling, Systems Engineering, 10 (4), 2007, 297-307.

Manthorpe Jr., W.H., "The Emerging Joint System-of-Systems: A Systems Engineering Challenge and Opportunity for APL," Johns Hopkins APL Technical Digest, Vol. 17, No. 3 (1996), pp. 305–310.

M. Miaer, Architecting principles for systems-of-systems, Proc INCOSE Sypm, 1996.

A. Sage, C. Cuppan, ON the systems engineering and management of systems of systems and federations of systems, Inform Knowledge Syst Management 2 (2001), 325-345.

US Air Force Scientific Advisory Board (USAF SAB). Report on system-of-systems engineering for Air Force capability development. https://acc.dau.mil/Get Attachment.