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**A System of systems Framework for the
Evaluation of Critical Infrastructures
-The Case of Changi International Airport**

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ABSTRACT

Critical Urban Infrastructures are always a crucial concern to any governments and their decision makers. Infrastructures based on the current demographic trend, future cities will provide residence for almost 70% of total global population in a few decades. However, we stand at a crossroad, that cities must change radically to achieve long-term sustainability and survivability. Shortage of energy, food and water resources, inadequate public transportation systems and other basic infrastructures, will constrain the potentials and diminish the quality of life in future cities. Moreover, natural disasters such as cyclone, earthquake and flooding and man-made disasters resulting from terrorism and negligence are emerging threats to the integrity of these critical urban infrastructures. How will we meet this immense challenge? The research aims at studying the challenges faced from a systems engineering (SE) and System of systems engineering (SoSE) perspectives on the issues of sustainability, resilience and design of urban critical infrastructure for future cities. It will come up with a framework to determine effectiveness of SoS approach on urban infrastructures and bring a usable conceptual tool for decision makers of future urban infrastructure. It is to go beyond the traditional engineering and management on large scale projects by using the System of Systems (SoS) approach.

The SoS framework consists of two main steps of diagnosis and hierarchical analysis that could be combined with performance measurement. This model can be applied to any large scale infrastructure project to help government key planners and decision makers take better decisions in terms of incremental development and expandability, resource allocation, national development and infrastructural economy.

The framework can apply on both existing and yet to be built systems. To validate the model Singapore Transportation system (NTS) will use as a test case with three main constituent systems of air transportation system (Civil

Aviation of Singapore-CAAS), land transportation system (The Land Transport Authority-LTA) and sea transportation system (The Maritime and Port Authority of Singapore-MPA). The special focus of this thesis will be on Singapore air transportation system, The Changi International Airport.

The proposed framework defines the relevant six SoS characteristics and fourteen evaluation attributes. The framework is further extended to a hierarchical model where different levels of SoS are identified. These levels are related to four categories of policy, economic, resource and operations.

To
my beloved wife,
Laleh

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Chapter 1 INTRODUCTION

Today's need for more capable, complex systems in a short period of time, is leading more organizations towards the integration of existing systems and new systems into network-centric, knowledge-based System of systems (SoS). All of these efforts need systematic approach and due to their complexity they are all SoS contexts. By analyzing such projects through SoS holistic view there will be effective changes in business strategies, opportunities to affect supply chain management, strategic policies, and even homeland security.

SoS firstly defined in defence projects that have the heterogeneous, distributed and integrated criteria. Recently it developed to be applied to civilian large scale inter-disciplinary development projects like Urban Infrastructures. Such large scale infrastructural projects usually developed in evolutionary stages upgrading and integrating existing systems with adding extended new systems. Large complex systems are not monolithic and their subsystems are often complex systems by their own.

A significant challenge of design within an SoS is determining the appropriate mix of independent systems to meet a set of needs or provide a set of services. Evolution of an SoS over time will be more efficient if design methods include making decisions about when to retire existing assets, when to add new assets, and when to upgrade assets with improved technologies; extensions of dynamic programming are needed for this. Systems of Systems are (and will be) designed and operated under uncertainties.

1.1 Problem Statement and Objectives

Future large scale infrastructure planning needs governments and their decision makers to make decisions for better efficient future development. Beside traditional systems engineering tools that been used through last decades, recently more complex and large scale problems face to the fast growing world. An alternative to have a better solutions and understanding of this paradigm could be System of systems approach.

The most important aim of this thesis is using the holistic conceptual SoS model to give the decision makers ideas in concept of System of systems for their decisions in area of large scale infrastructures. In such projects using large amount of money and resources, importance of proper and exact time as internal forces and global economy and policies as external forces makes it more complex.

Through this research, Singapore air transportation will be study and analyzed by defining related SoS characteristics.

The objective of this research is to answer these questions:

- What are the definitive definitions of SoS in different context? i.e. Critical infrastructure, defence ...
- To what extent the existing of critical infrastructure exhibit SoS characteristics?
- Do these characteristics contribute to superior investment and operational performance of critical infrastructures?

Test bed is Changi Airport that related to Air transportation, finalized SoS framework could be apply to Land Transportation Authority (LTA), and Port of Singapore Authority (PSA) as sea transportation component of Singapore National Transportation System (NTS).

1.2 Scope

Scopes of this research are as follow:

- Study and synthesize, SoS related literatures with a focus on large scale Infrastructure development.
- To develop a SoS framework to assess SoS characteristics and find the SoS compatibility of large scale projects
- Using Singapore Air Transportation system and its constituent systems to validate and develop the SoS framework model

1.3 Methodology

This research on SoS approach to critical infrastructures with an improved understanding of the implication of policy decisions, resource allocations, and infrastructure investment strategies, through the capture of emergent behaviors and interdependencies provides decision makers a wider view for coming decision makings of future cities. The sequences of methodology used in this research are as follow:

- Using literature review related to both SoS and critical infrastructure to develop definitive definitions of SoS
- Develop a framework using SoS characteristics and attributes.
- Validate SoS framework, using Singapore transportation system.

1.4 Organization of Chapters

This research is organized around the framework required to implement the concepts described above.

Chapter Two presents related SoS research in different domains that were used to address the problem. In this chapter the SoS characteristics will be developed to define the SoS attributes.

Chapter Three presents SoS hierarchy and categories that will be used in the SoS framework.

Chapter Four presents SoS applications for better understanding of the SoS concept.

Chapter Five presents the framework and its different steps. SoS characteristics and attributes will be described.

Chapter Six details a study that provides evidence concerning the validity of the framework.

Chapter Seven collects good lessons that could be learned by study of Changi Terminal T3 development phases.

A conclusion will end this study on large scale infrastructural development and show the achievement of this study in chapter eight.

Chapter 2 LITERATURE REVIEW

2.1 What Is A System?

To understand “what is a SoS?”, first it is necessary to know the meaning of “what is a System?”.

A system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective.(DOD 2001) or a set of interrelated components working together toward some common objective.(Kossiakoff and Sweet 2003)

2.2 What Is A Large Scale System?

Jamshidi (2003): A system is sometimes considered to be large scale if it can be partitioned or decoupled into a number of subsystems, that is, small-scale systems. Another viewpoint is that a system is termed large scale if its dimensions are so great that conventional techniques of modeling, analysis, control, design, optimization, estimation, and computation fail to give reasonable solutions with reasonable efforts. A third definition is based on the notion of centrality. Until the advent of large-scale systems, almost all control systems analysis and design procedures were limited to having system components and information flow from one point to another localized or centralized in one geographical location or center, such as a laboratory. Thus, another definition is a system in which the concept of centrality fails. This can be due to a lack either of centralized computing capability or of a centralized information structure. Large-scale systems appear in such diversified fields as sociology, business, management, the economy, the environment, energy, data networks, computer networks, power systems, flexible space structures, internet-based systems, transportation, aerospace, and navigational systems.

2.3 What Is A Family of Systems?

A family of systems (FoS) is basically a grouping of systems having some common characteristic(s). A family of systems does not create capability beyond the additive sum of the individual capabilities of its member systems. Actually a family of systems is a grouping of systems with common characteristics and basically does not acquire new properties or capabilities as a result of grouping.

2.4 What Is A System of systems?

There is not a single, widely accepted definition of System of systems (SoS), although it has been in use for several years. Keating (Keating, Rogers et al. 2003) and his co-authors describe System of systems as a metasystems that “are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operations, geography and conceptual frame”. On the other hand, a SoS is a collection of task-oriented and dedicated systems that bring together their individual resources and capabilities together to obtain a new meta complex system. A System of systems is comprised of individual systems capable of independent operation. Using multiple systems in collaboration can provide capabilities well beyond those available from a single system. Further, the ability for each constituent system to operate independently can provide increased robustness for the overall System of systems. However, these aspects provide an additional level of complexity in determining which systems provide which contributions to the overall performance. (Crossley 2004)

Boardman (2006) introduced five distinguishing characteristics to recognize or realize a System of systems (SoS), which are: Autonomy, Belonging, Connectivity, Diversity and Emergence, that will explain later.

Systems-of-systems should be distinguished from large but monolithic systems by the independence of their components, their evolutionary nature, emergent behaviors, and a geographic extent that limits the interaction of their components to information exchange.(Maier 1998)

Based on literature survey on System of systems, there are numerous definitions in different domains. Some of the most famous definitions categorized in original (fundamental) and synthesize group. Most of the recently definitions belong to second group that will be presented in a chronological order.

2.5 Original Definition of SoS

Ackoff (1971) believed that there should be a generally accepted framework to convergence all of the definitions made by researchers about the systems. Total system performance derives from relationships between parts of the system. It is very important how the parts interact and fit together. Ackoff defined 32 system related terms and is one of the pioneers of SoS terminology. Most of other scientists refer to his definitions to have a description for SoS, also to build a general architecture for SoS.

Eisner (1993): 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 definition is a fundamental for any large, distributed, governmental projects.

Principal characteristics for System-of-systems

Maier (1998) presented a basic set of architecting principles to assist design of SoS. As some examples for SoS he mentioned integrated air defense networks, the Internet, intelligent transport systems, and enterprise information networks. He said: Systems-of-systems should be distinguished from large but monolithic systems by the independence of their components, their evolutionary nature, emergent behaviors, and a geographic extent that limits the interaction of their components to information exchange. With this categorization systems are divided to two categories: System of systems and Collaborative systems. A System of systems is a system that its components fulfilled valid purposes in their own right and continued to operate to fulfill those purposes if disassembled from the overall system. In Collaborative systems the components are managed (at least in part) for their own purposes rather than the purposes of the whole.

Five principals of SoS characteristics are:

- **Operational Independence of the Elements:** If the system-of-systems is disassembled into its component systems the component systems must be able to usefully operate independently. The system-of-systems is composed of systems which are independent and useful in their own right.
- **Managerial Independence of the Elements:** The component systems not only can operate independently, they do Manage independently. The component systems are separately acquired and integrated but maintain a continuing operational existence independent of the system-of- systems.
- **Evolutionary Development:** The system-of-systems does not appear fully formed. Its development and existence is evolutionary with

functions and purposes added, removed, and modified with experience.

- **Emergent Behavior:** The system performs functions and carries out purposes that do not reside in any component system. These behaviors are emergent properties of the entire system-of-systems and cannot be localized to any component system. The principal purposes of the systems-of-systems are fulfilled by these behaviors.
- **Geographic Distribution:** The geographic extent of the component systems is large. Large is a nebulous and relative concept as communication capabilities increase, but at a minimum it means that the components can readily exchange only information and not substantial quantities of mass or energy.

There is a clarification with the definition proposed by (Shenhar and Bonen 1997), that named it Array and it defined: A large widespread collection or network of systems functioning together to achieve a common purpose.

Maier believed in some large array type systems the components do not necessarily provide the overall purpose. He approved it with this example: In a highly distributed sensor surveillance network it may be impossible for any of the individual sensor nodes to perform a useful surveillance function. The computers and components that make up the network do something when disconnected from the supersystem, but that remaining function is distinct from that of the supersystem. In contrast, many components of an integrated air defense system can still perform an air defense function when disconnected, albeit at a reduced level.

Beside the components relationship network and their overall purpose that considered as operational concepts of a SoS there is an additional dimension, that of managerial control, is critical to identifying appropriate characteristics of

a SoS. Maier categories System of systems to three groups in classification of managerial control: Directed, Collaborative and Virtual.

Directed systems are those in which the integrated system-of-systems is built and managed to fulfill specific purposes. Centrally managed, for example, an integrated air defense network is usually centrally managed to defend a region against enemy systems, although its component systems may operate independently.

Collaborative systems are distinct from directed systems in that the central management organization does not have coercive power to run the system. The Internet is a collaborative system.

Virtual systems lack a central management authority. Indeed, they lack a centrally agreed upon purpose for the system-of-systems. Examples are: the World Wide Web and national economies.

He brought three examples to explain principles of System of systems: Integrated Air Defense, Internet and Intelligent transportation systems. A clear example of SoS is Integrated Air Defense. It composes of geographically dispersed network of semi-autonomous elements. These include surveillance radars, passive surveillance systems, missile launch batteries, missile tracking and control sites, airborne surveillance and tracking radars, fighter aircraft, and anti-aircraft artillery. All units are tied together by a communications network with command and control (Manage) applied at local, regional, and national centers.(Maier 1998)

Internet is the global communication network of computers that in managerial classification, it is an example of a collaborative System of systems. It is a collaboratively exchange of information between components, that they maybe sub networks and major computer sites by their own. This exchange took place at protocol level and from managerial angle of view there is no central authoritative coercive power to manage this data transfer. Coercive

power emerges through agreements among major sites to block traffic and sites observed to misbehave.

Intelligent transport Systems is an example of very large, collaborative System of systems. For instance, Advanced Traveler Information Services (ATIS) and Advanced Traffic Control Systems (ATCS) are two good example of implementation of Systems of Systems. The main point in System of systems is Communication. Since the elements of a system-of-systems are substantially independent, and cannot exchange significant matter and energy, they collaborate only through information exchange.(Maier 1998)

2.6 Synthesize Definition of SoS

Manthorpe (1996) in Military application, with primary focus on Information superiority defined SoS as: In relation to joint war fighting, System of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR) Systems.

Kotov (1997) in Private Enterprise with a focus on Information Systems defined SoS as: Systems of systems are large scale concurrent and distributed systems that are comprised of complex systems.

Lukasik (1998) in Education application with a primary focus on Education of engineers to appreciate systems and interaction of systems defined as: SoSE involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure.

Pei (2000) in Military application with a primary focus on Information intensive systems integration defined SoS as: System of systems Integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios.

Sage and Cuppan (2001) in Military application with a primary focus on evolutionary, Sage defined SoS as: Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development.

Carlock and Fenton (2001) in the same field of Kotov, Private Enterprise and have a special approach on Information intensive systems, defined SoS as: Enterprise Systems of Systems Engineering is focused on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis.

There are many problems today that cannot be solved with traditional monolithic systems.(Despotou, Alexander et al. 2003) Due to the need to integrate new and old technologies, to fully exploit modern autonomous technologies and also to make the most of legacy systems a new paradigm is necessary. These emergent classes of systems, built from components that are large-scale systems in their own right, are best described using a new model. In such a System of systems (SoS) model the interactions amongst elements are as important as the function of the elements themselves. Example systems that embody the structure and features of a System of systems are:

- Air traffic control
- Automated highway systems
- Integrated air defence
- Unmanned aerial vehicles

Bar-Yam (2005) believed even while there have been many discussions, SoS is in its infancy and there is not a commonly accepted definition for it. Professions and academia working on different fields, produced there own related definitions.

Boardman (2006) introduced five distinguishing characteristics to recognize or realize a System of systems (SoS), which are: Autonomy, Belonging, Connectivity, Diversity and Emergence. Nature of a system's composition makes the principal differentiation between a system and a SoS. To distinguish a system, there are many tools in systems engineering, but to differentiate a SoS we should defined new concepts. With study of these five characteristics that will explain later we can distinguish SoS.

Autonomy

Definition: The ability to make independent choices; The right to pursue reasons for being and fulfilling purpose through behaviors.(Boardman 2008)

Motivation: Legacy systems are indispensable to a SoS; the SoS has a higher purpose than any of its constituent systems, independently or additively.

Provenance: managerial and operational independence.

Each legacy system that is envisaged to become a constituent system in the SoS must be accorded autonomy, the right to pursue reasons for being and fulfill purposes through behaviors.

After introducing Holon by Smuts(Smuts 1926) which later was explained in more detail by Koestler as bring that which is both Whole and part, Boardman believed that a SoS cannot be so called on the basis of structure alone, including hierarchies and holarchies. Koestler defines holarchy to be a hierarchy of self-regulating holons that function (a) as autonomous wholes in supraordination to their parts, (b) as dependent parts in subordination to controls on higher levels and (c) in coordination with their local environment. (Koestler 1967) examines the notion that the parts of the human brain-structure which account for reason and emotion are not fully coordinated. This kind of deficiency may explain the paranoia, violence, and insanity that are central parts of human history, according to his analysis of the human

predicament.”(Koestler 1967). SoS must qualify on the basis of dynamics.(Boardman 2008)

To understand better there are two examples here, Brake in an automobile and Payroll system in a company. Regarding analyzing the Autonomy of payroll system we find it should be a part of an enterprise system, and it is not a system by its own. The brake system is supposed to be a part of whole automobile system. Because it designed to perform deceleration of a whole system that here is a vehicle, and it is a need of a system that satisfied by a part. It serves no purpose of its own.(Boardman 2006)

Belonging

Definition: Happiness found in a secure relationship.(Boardman 2008)

Motivation: Legacy systems may need to undergo (radical) change in order to serve in a SoS.

Provenance: Shared mission.

Considering legacy systems, there are two new realities: the problematique and the envisioned SoS. The SoS cannot translate from conceptual reality into physical reality without the constituent systems belonging. The parts of a system (that is, not a SoS) have no choice in the matter of belonging since they have no reason for existence and no dynamics to contribute without belonging. In a SoS the parts, also wholes and therefore holons, are integrable, that is, capable of being integrated. It is not about a the system as such but about the SoS capabilities for resolving or addressing the problematique. Hence belonging becomes as core competence or stratagem available to the SoS for dealing with the problematique.(Boardman 2008)

In study of SoS we face some existing systems be sides new ones. These are parts of a whole system that are systems by its own.[Legacy Systems] To analyze a SoS we should have permit to answer the essential following

questions. Making relationship between legacy systems with new autonomous systems that persuade the value of all is a cost consuming process .Why should these costs be paid? What is the RoI, the overall benefit? What is the value proposition? Do I lose my autonomy? Shall I cease to be a system, and become merely a part? If my original purpose is still valid, and I am not delinquent in fulfilling it, how can I ethically decide not to be a system? The main point is the existence of the SoS will enhance the value of the system's purpose, exalt the role of the system, shoes belonging makes achievement of the whole system purpose more likely and more effective.(Boardman 2006)

Connectivity

Definition: The ability of a system to link with other systems.(Boardman 2008)

Motivation: Legacy systems targeted for an envisioned SoS are very likely to be highly heterogeneous and unlikely to conform to a priori connectivity protocols; the SoS places a huge reliance on effective connectivity in dynamic theaters of operations.

Provenance: Interdependence, distributed, networked, multiple solutions, interoperability.

Most designed systems require the relationships between elements to be designed simultaneously with the design of the elements themselves. Connectivity has to do with a lot more than just topologies and protocols and interoperability standards, although it does address these practical matters, and its more concerned with the agility of structures for essential connectivity in the face of a dynamic problematique that defies prescience.(Boardman 2008)

We are faced with the need to create connectivity (interoperability) amongst the legacy systems and possibly additions of new systems to the SoS. It is the connectivity between subsystems and newly added subsystems that are

not appear at its surface or system boundary. This statement of connectivity is a dynamic connectivity between SoS components.(Boardman 2006)

Diversity

Definition: Noticeable heterogeneity; having distinct or unlink elements or qualities in a group; the variation of social and cultural identities among people existing together in an operational setting. (Boardman 2008)

Motivation: Legacy systems targeted were most unlikely to have been purposed to work together prior to targeting the envisioning of the SoS; the SoS can only achieve its higher purposes by leveraging the diversity of its constituent systems.

Provenance: Independence, diversity, heterogeneous.

We have KISS in traditional systems engineering. KISS stands for “ Keep it Simple, Stupid”. But in an age when complex systems give rise to simple patterns and simple systems produce complex behavior, perhaps it is time for diversity to be seen less as a problem and more as an opportunity.(Waldrop 1992) Given that legacy systems from the beginning, present a given and possibly great diversity. The opportunity for the SoS is to increase connectivity, which probably translates into standard protocols and specific architectures or topologies, an imperative for uniformity and increased diversity. Diversity, through a variety of viewpoints, processes, technologies, and functionalities, ensures richness, and the SoS must be able to leverage this, in an unencumbered fashion. (Boardman 2008)

The law of requisite variety (Ashby 1957) is very important for a system. It says: to maintain stability of a system in an operating environment the number of degree of freedom should be the same as the number of external forces that could apply to the system. So to have a live system working for a long time we should have diversity of species in our system. A SoS should be incredibly

diverse in its capability as a system compared to the rather limited functionality of a constituent system limited by design.(Boardman 2006)

Emergence

Definition: The appearance of new properties in the course of development of evolution. (Boardman 2008)

Motivation: A boundary is indispensable to a system; all systems are emergent; emergence requires a well-defined boundary; a SoS has dynamic boundaries but always clearly defined; therefore, a SoS should be capable of developing an emergence culture with enhanced agility and adaptability.

Provenance: Evolving, intelligence, synergy, dynamic, adaptive.

When parts and their relationships are assembled together, what emerges is the system. All systems are emergent. The properties, behaviors, and purposes attributed to systems can also be said to be emergent. There is an example of automobile, the purpose is: transporting goods and people across reasonable distance and terrains, safely comfortable, and in timely fashion. This is the emergence of whole system. But each part of automobile has its own emergent properties. For example, the power train to provide propulsion, the wheels to provide traction, and the steering to provide guidance control. A system provide a response to a set of predetermined requests, that is threats or opportunities arising from the environment in which it operates. By contrast, a SoS is an anticipatory responder having an priori undetermined and unknowable range of responses subordinated to auxiliary mechanisms for anticipation, including disturbing the ability of the environment to pose threats or limit opportunity.(Boardman 2008)

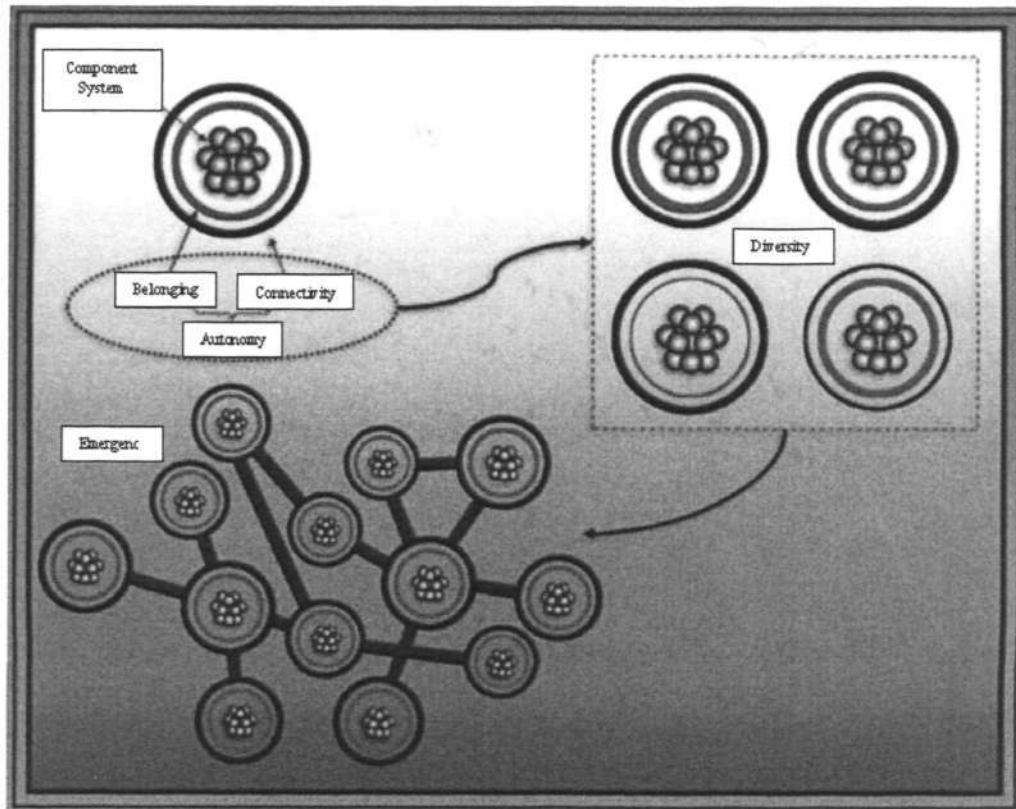


Figure 2-1 Biology of systems(Boardman 2008)

SoS 'whole sum' is different with 'the sum of the parts'. So in a SoS we achieve some purposes that is not achievable in simple systems. In a system, emergence is deliberately and intentionally designed in. But in a SoS emergent capability design and implement through other factors, like: autonomy, belonging, connectivity and diversity.(Boardman 2006)

To differentiate between a system and a SoS the following table presented:

Table 2-1 Differences between a system and a SoS (Boardman, 2008)

Element	System	System of systems
Autonomy	Autonomy is ceded by parts in order to grant autonomy to the system	Autonomy is exercised by constituent systems in order to fulfill the purpose of the SoS
Belonging	Parts are akin to family members; they did not choose themselves but came from parents, and minimum connectivity among major subsystems.	Constituent systems choose to belong on a cost/benefits basis; also in order to cause greater fulfillment of their own purpose, and because of belief in the SoS supra purpose.
Connectivity	Prescient design, along with parts, with high connectivity hidden in elements, and minimum connectivity among major subsystems.	Dynamically supplied by constituent systems with every possibility of myriad connections between constituent systems, possibly via a net-centric architecture, to enhance SoS capability.
Diversity	Managed i.e. reduced or minimized by modular hierarchy; parts' diversity encapsulated to create a known discrete module whose nature is to project simplicity into the next level of the hierarchy	Increased diversity in SoS capability achieved by release autonomy, committed belonging, and open connectivity.
Emergence	Foreseen, both good and bad behavior, and designed in or tested out as appropriate	Enhanced by deliberately not being foreseen, thought its crucial importance is, and by creating an emergence capability climate, that will support early detection and elimination of bad behaviors.

There has been, especially in military circles, much discussion of creating a "total force effect" from new and existing systems, in such a way that the resultant system surpasses the sum of the individual components.(Despotou,

Alexander et al. 2003) They defined SoS via citing the previous definition as follow:

Based on the communications infrastructure between the elements of the SoS: large scale concurrent and distributed systems, the components of which are complex systems themselves (e.g. enterprise networks)(Kotov 1997). Here the idea is: The elements are perceived to be complex systems, which by communicating with other complex systems form a SoS. But it does not provide clear boundaries between SoS and Systems that are simply complex.

SoS is a dependable system composed of autonomous systems. The purpose of the SoS is to provide a set of enhanced or improved 'emergent' services, based on some or all of the services provided by participating component systems(Periorellis 2002). In this definition Periorellis has identified the multi-role nature of the SoS elements and the different types of behaviour that emerge from the combination of their Individual capabilities. Also Periorellis definition satisfied many characteristics of a SoS which have been identified by the US Department of Defence as follows:

- Exceedingly Complex
- Large number of components
- Sophisticated or ambiguous nature of relationships among elements
- Lack of specificity of components
- Low degree of organization within the system
- Geographically dispersed

US Department of Defence (DoD) research development and acquisition office defined SoS as:(Clare 2000)

An assemblage of components which individually may be regarded as systems and which possess two additional properties:

1) Operational Independence of its components: If the SoS is disassembled into its component systems, the component systems must be able to operate independently. That is, the component systems are capable of fulfilling customer or operator purposes on their own.

2) Managerial Independence of the Components: The component systems not only can operate independently, they do operate independently. Component systems are separately acquired and integrated, and maintain a continuing operating existence independent of the SoS.

So DoD discriminate between a complex Systems and a Systems of Systems. Despotou defined an extracted number of characteristics for SoS as follow:(Despotou, Alexander et al. 2003)

- Autonomy
- Decentralised Control / Collaboration
- Heterogeneity
- Complexity
- Adaptability
- Dynamic reconfiguration
- Emergent behaviour
- Dependability

Despotou et al (Despotou, Alexander et al. 2003) defined concluded meaning of SoS: a System of systems is an organized complex unity assembled from distributed autonomous systems (capable of independent provision of services) collaborating to achieve an overall higher system purpose.

Despotou describe each of their defined characteristics and it brings here the main point of their words:

Autonomy

It means “the condition of being controlled only by its own laws, and not subject to any higher one” in oxford dictionary.(Oxford 1989) Autonomy is more than the only independent operation of component systems of a SoS (Maier 1998). Autonomy of a SoS is having the free will to make its intelligent choice. The US Department of Defence identified ten levels of autonomy for its projects that mostly can be considered as a SoS.

- Remotely Controlled Systems (conventional “dull” systems)
- Real time health diagnosis (self awareness)
- Adaptation to failures/weather (data loss tolerance)
- Execution replanning (e.g. route for UAVs, intelligence)
- Group coordination (emergent behaviour)
- Group tactical replanning (shared awareness state)
- Group tactical goals
- Distributed control
- Group strategic goals
- Fully autonomous systems

It is obvious that an increased level of autonomy thus entails a reduced level of control. Mostly in military project human intervention may also be necessary for final weapons release authorization. So a system could not be fully autonomous in this area to bring safety. There is also a political question to solve and this is “how much autonomy is politically acceptable?” Most researchers appear to agree that the ideal level of autonomy is one that allows the system to perform almost all functions without human intervention, but ensures that a human controller always retains final authority on decisions of significant consequence, such as weapons release.(Lawson 1998)

Collaboration & Decentralized control

In a SoS all component systems need to communicate with each other within our SoS, either directly or via a third party and due to this relations these SoS are collaborating type.(Maier 1998) it means they will rely on data that was provided by other systems. An advantage of decentralized control is to reduce the burden on central command. On the other hand reliance on a central controller creates a single point of failure.(Gabbai 2002)

As a good example of collaboration and decentralized control, a group of armed UAVs with a joint mission can be considered. destroying an specified target is the mission and all UAVs should arrive in the same time as a group, not to be easily destroyed.(Despotou, Alexander et al. 2003)

In particular, decentralizing the control of every aspect of operation and designing the system to collaborate, bring beneficial emergent behaviour. It has been shown that emergent behaviour can lead to increased SoS robustness. Reliance on a central controller creates a single point of failure.(Gabbai 2002)

Heterogeneity, open systems

Open systems as it sounds, means a combination of diverse range of component systems that make a SoS. Systems interact with each other through standardized interfaces. In such open SoS, any new component system can easily enter the SoS, just through standardized interfaces to exchange data with other components. We should have new tools and techniques to easily enter new system components to a dynamic SoS.

Complexity

Weinberg (1975) said many components with a very large number of interconnections between the component systems make an SoS too complex to analyze completely. But they are too organized to be treated in a purely statistical fashion.

Sussman (2000) mentioned the level of complexity of a system depends on the number of interconnections. The complexity of a system can be quantified in terms of the number on interconnections between the parts and the information contained in those interconnections.

In most of Systems complexity is a weak point and analyzers try to make them complicated to be solvable. It is difficult to describe behaviour of a complex SoS, because a change to one component of the system may affect other components.

Adaptability

Adaptation means system change in order to accommodate changes in its environment. Adaptation involves: Ability to recognize a change in the environment, Ability to determine the changes that need to be made to the system, according to the change in the environment Ability to effect the change in order to generate the new system configuration. (N. Subramanian 2001)

Adaptability has to give SoS the ability to tolerate changes in its environment only, and not changes of its own structure. Adaptability is deferent with dynamic reconfiguration through their impact on design and hence on the lifecycle.(N. Subramanian 2001) The aim of adaptability is the continuity of service even when the environment is beyond specifications. In other hand, adaptability is related to planning and scheduling of the tasks of a SoS in order to compensate for the environmental changes.

Dynamic reconfiguration

In this SoS characteristic the term “failsafe” brings a valuable parameter of the component systems. A failsafe state guaranteed when a failure occurs, not to result in an accident. However in a SoS because of its complexity and large number of components there may not be a failsafe state. instead , in case of a failure, the SoS needs to reconfigure by detecting and removing the faulty element.

Nace (2001) The key insight of such reconfiguration is to respond to a failure, resynthesise the system in such a way as to maximize system functionality. Removing a component in a SoS depends on the role of component system within the SoS.

The main advantage of dynamic reconfiguration is the run time mitigation of failures and the continuous availability of SoS.

Emergent Behaviour

Emergent behaviors are unpredictable behaviors of a large number of components, making SoS, result of interactions between components within the SoS which cannot be predicted from observation of any component n its own.

Resnick (1996) An example of emergent behaviour is flocking in birds; a flock has no 'leader bird', but each bird in the flock follows certain simple rules, altering its behaviour based on the movements of the other bird around it. The overall shape and movement of the flock emerges from this behaviour by individual birds.

Dependability

Mario (1997) The system's characteristic that justifies placing one's reliance on it. So reliability and availability are the two certain attributes that the system needs to exhibit.

Shelton (2002): *Dependability is a term that covers many system properties such as reliability, availability, safety, maintainability and security.*

In different system's domain, the developer may focus on different attributes of dependability such as safety in airlines, reliability in military and space systems, security in networks and communications and data integrity in databases. There is no single, widely accepted, definition of dependability. SoS

elements are viewed as ‘black boxes’ which can be independent systems having a certain degree of autonomy, collaborating to achieve the SoS top level goals.

Dependability is like an umbrella, covering many attributes, such as safety, availability, reliability and performance.

As shown in Table 2-2 a list of more cited SoS related scholars presented. SoS characteristics were repeatedly being studied and applied by many scholars in different domains over the last two decade. The fundamental of the SoS framework in this research is presenting definitive definitions related to large scale complex systems. As it is completely clear in the following table the most powerful characteristics is the Maier’s five principles. Other researchers just synthesize them and add some other characteristics related to their domain of study.

Table 2-2 A list of SoS domains and characteristics in chronological order

Author and Year	Domain	Key points
(Ackoff 1971)	Systems Engineering theory	Total system performance SoS terminology
(Eisner, McMillan et al. 1993)	Software Engineering	Geographically distributed Large Scale Systems Centrally directed Particular purpose
(Shenhar 1995)	SoS General Concept	Geographically distributed Common purpose Network of systems Large scale
(Manthorpe 1996)	Military & Defence	Interoperability Synergism
(Maier 1996)	SoS General Concept (The most useful primary characteristics)	Large and complex Operational independence Managerial independence Evolutionary development Emergent behavior Geographically distribution
(Kotov 1997)	Private Enterprise	Large scale Concurrent Distributed Complex
(Lukasik 1998)	Education	Integrated Evolutionary
(Krygiel 1999)	Military & Defence	Diversity Network of systems Synergism Interoperability Integration Emergent behavior.
(Pei 2000)	Military & Defence	Integration Interoperability Enhance performance Optimization
(Carlock and Fenton 2001)	Private Enterprise	Mix of legacy and new systems Complex Seamless interoperability Acceptable performance Strategic planning Investment analysis

(Sage and Cuppan 2001)	Military & Defence	Diversity Existing and legacy systems Operational independence Managerial independence Evolutionary development Emergent behavior Geographically distribution
(Periorellis 2002)	Systems integration	Autonomous Emergent behaviour Multi role Complex
(Clare 2000)	Military & Defence	Complex Physically widely dispersed Ambiguous nature of relationships Operational and managerial independence
(Gupta 2003)	Military & Defence	Leadership Highly Coordination Motivation Presence of Lead System Integrator
(Bergey, O'Brien et al. 2003)	Supply & demand, Product line	Diversity Complexity Lead system integrator central management Authority Synergism
(Keating, Rogers et al. 2003)	SoS General Concept	Metasystems Autonomous Interrelation Complexity Diversity Geographically distribution Synergism Emergent behaviour
(Despotou, Alexander et al. 2003)	Military & Defence	Autonomy Decentralised control Heterogeneity Complexity Adaptability Dynamic reconfiguration Emergent behavior Dependability
(Kuras and White 2005)	Complexity	Synergism Evolutionary development Independent management Independent operations Emergent behaviour Geographically distributed

(Bar-Yam 2005)	Biological Sociology Military	Evolutionary development Emergent behavior Self organization Adaptation Complex systems Individual specialization Synergy
(Lane and Valerdi 2005)	Cost modeling & Estimation	Emergent behavior Complex Interoperable systems Mix of exiting, new, or diverse systems
(Northrop, Feiler et al. 2006)	Software Engineering	Independent Synergism Inconsistent New paradigm for policy and acquisition Erosion of the people/system boundary Evolutionary behavior Decentralized data, development, evolution, operational control
(Boardman 2006)	SoS General Concept	Autonomy Emergent behavior Connectivity Diversity Belonging
(Sheard and Mostashari 2008)	Complexity	Integration of independently Rapid evolution Multiple disparate stakeholders Distributed development Complexity
(Lewis, Morris et al. 2008)	SoS General Concept	Centralization Stakeholders diversity Operational independence Diversity Volatility Emergence Evolutionary

2.7 SoSE versus SoS

System of systems engineering (SoSE) deals with planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a System of systems capability greater than the sum of the capabilities of the constituent parts (systems). It is a top-down, comprehensive, collaborative, multidisciplinary, iterative, and concurrent technical management process for identifying System of systems capabilities; allocating such capabilities to a set of interdependent systems; and coordinating and integrating all the necessary development, production, sustainment, and other activities throughout the life cycle of a System of systems. The overall objective for developing a System of systems is to satisfy capabilities that can only be met with a mix of multiple, autonomous, and interacting systems. The mix of constituent systems may include existing, partially developed, and yet-to-be-designed independent systems. Systems of systems should be treated and managed as a system in their own right, and should therefore be subject to the same systems engineering processes and best practices as applied to individual systems. (DOD 2006)

SoSE presents new challenges that are related to, but distinct from, systems engineering (SE) challenges. By understanding these differences, appropriate methods, tools, and standards can be crafted in an intelligent manner. The importance of having a group of systems working together as opposed to a single system is to increase the capability, robustness, and efficiency of data aggregation. In the U.S., major aerospace and defense manufacturers, include some version of “large-scale systems integration” as a key part of their business strategies. (De Laurentis, Dickerson et al. 2007)

The engineering of a System of systems differs from the engineering of a single system.(DOD 2006) A System of systems is a set or arrangement of multiple, autonomous, and interacting systems that are related or connected to provide a given capability. The loss of any constituent systems will significantly degrade the performance or capabilities of the whole. The

development of a System of systems solution will involve trade space between the systems as well as within an individual system's performance. The consideration of System of systems engineering should include the following factors or attributes:(DOD 2006)

- Larger scope and greater complexity of integration efforts;
- Collaborative and dynamic engineering;
- Engineering under the condition of uncertainty;(mostly in military issues)
- Emphasis on design optimization;
- Continuing architectural reconfiguration;
- Simultaneous modeling and simulation of emergent System of systems behavior; and
- Rigorous interface design and management.

2.8 System of systems versus Family of Systems

As mentioned in section 2.3, a family of systems (FoS) consist of different systems having some common characteristic(s). This military base definition is presented for better categorization of systems and it does not create capability beyond the additive sum of the individual capabilities of its member systems. Actually in a FoS contrary to SoS, systems are not directed to integrate with other systems to achieve a higher goal. On the other hand in FoS sum of the whole is equal to sum of the individual systems.(DOD 2006)

As shown in Figure 2-2 systems with some common characteristics are in a category named FOS. On the other hand SoS constituent systems have a share mission to achieve a common goal that summation of them cannot bring the

goal to whole system. As presented in the figure constituent systems of a SoS may selected form different FoS that means they belong to different domains.

To understand better suppose a family of missiles or aircrafts, each system in a family of systems may belong to a domain or a specified product line. In a family of systems there is not a holistic synergy like it is dominant in a System of systems. Individual systems within a family may be incorporated into one or more SoS, or may not be part of any SoS. Systems in a family have a share common characteristic, missions, functions or inheritance. SoS are developed to provide a desired capability by integrating the functionality of individual systems from various families.

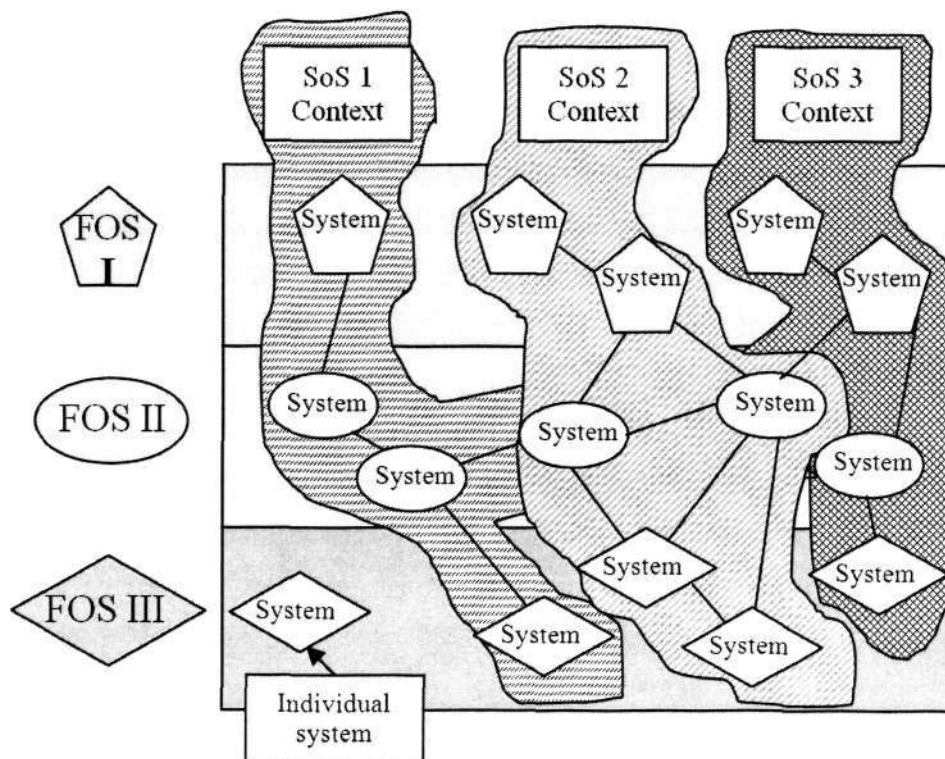


Figure 2-2 SoS versus FoS

Chapter 3 HIERARCHY AND CATEGORIES OF SoS

DeLaurentis and Callaway (2004) defined system-of-systems problems as a multiple heterogeneous distributed systems including policies and economies as well as technologies that cause complexity. It makes it hard for decision makers to decide. They should plan the best route through a web of possible futures with incomplete map. DeLaurentis believed we need a new discipline to teach people how to think because there is a lack of systematic thinking at the basic level about how to address the challenges in SoS related issues. DeLaurentis recommends that intellectual, financial, and institutional resources should be invested for the purpose of initiating and nurturing a field of study that will enable us to better address this important type of problem.

Decision makers require more complete maps and tools that provide the appropriate analysis of complex systems with a large number of intersystem interdependencies. The concept of “horizontal thinking” becomes relevant, which is to include elements of the various system analysis capabilities in a new, more coherent approach that is effective for reckoning with this emerging problem type, often called system-of-systems.

He presented an unambiguous lexicon, as an example that is in two major structures (categories of systems and levels of hierarchy) as shown below. The categories highlight one important distinguishing trait of system-of-systems problems: the heterogeneous mix of engineered and sentient systems together in one problem setting. For each category, there is a hierarchy of components. To avoid the confusion with ambiguous derivations (e.g., system \rightarrow system-of-systems \rightarrow architecture), the lexicon employs the unambiguous use of Greek symbols to establish the hierarchy, Alpha (α), Beta (β), Gamma (γ), Delta (δ) and Epsilon (ϵ) which indicate the relative position within each category.

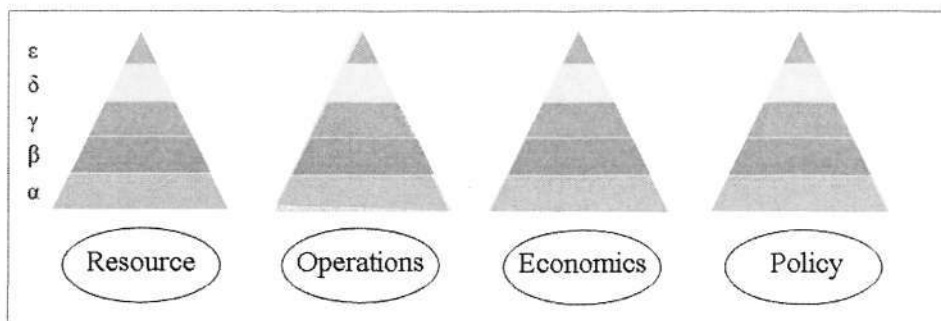


Figure 3-1 Categories and Hierarchy : An unfolded Pyramid Unifying the Lexicon(DeLaurentis and Callaway 2004)

Table 3-1 Categories of lexicon (DeLaurentis and Callaway, 2004)

Categories	Descriptions
Resources	The physical entities that give physical manifestation to the system-of-systems
Operations	The application of policies/procedures to direct the activity of physical entities
Economics	The non-physical, sentient systems that give a “living system” character to the operation of the physical entities in a market economy
Policies	The external forcing functions that impact the physical & non-physical entities

Table 3-2 Levels of lexicon (DeLaurentis and Callaway, 2004)

Levels	Descriptions
Epsilon(ε)	Collections of ε -level systems, organized in a network.
Delta (δ)	Collections of δ-level systems, organized in a network.
Gamma (γ)	Collections of γ-level systems, organized in a network.
Beta (β)	Collections of β-level systems, organized in a network.
Alpha (α)	The base level of entities, for which further decomposition will not take place. Alpha level components can be thought of as building blocks.

One initial reflection on this framework is that it highlights an important point about system-of-system maps: the evaluation of an individual entity at its own level is of less import than how it affects the higher level organization for which it is a member. Thus, the probability of possibilities should be evaluated at the γ and δ level which, incidentally, are also the levels where the most critical decisions arise. For system-of-systems, this will require extensions beyond the bounds of traditional systems engineering or systems analysis.

DeLaurentis (DeLaurentis and Callaway 2004) tried to describe his hierarchical model with an example. Application of Hierarchical SoS perspective in National Transportation System. He mentioned: The overarching issue is that the National Transportation System (NTS) is indeed a complex system, both in the colloquial and technical sense of the word. Complexity in the NTS stems primarily from three properties: the heterogeneity of constituent systems, the distributed nature of these systems, and the deep uncertainty in exploring its future state. NTS is in δ level, all kinds of transportation systems in a nation that help us to reach the main goal in transporting of people and goods in an efficient way, like Air, Land, Sea, are in γ level, all main components of each Transportation mode related to γ level are in β level, and in α level that is the lowest level subcomponents of β level are positioned. The variety of decision makers involved in transportation can be identified, engaged, and included in the discussion. Through subsequent modeling, the probabilities for solutions at the γ - or δ -levels can be formed by aggregating the α - and β -level entities. In the table bellow the various levels and categories of NTS are illustrated.

Table 3-3 Understanding of Levels and Categories in Case of NTS (DeLaurentis and Callaway, 2004)

	Resources	Operations	Economics	Policy
α	Vehicles & infrastructure (e.g., aircraft, truck runway)	Operating a resource, (aircraft, truck, etc.)	Economics of building/operating/buying/selling/leasing a single resource	Policies relating to single-resource use (i.e., no. of attendants per passenger for vehicle type)
β	Collection of resources for a common function (an airport, etc.)	Operating resource networks for common function (e.g., airline)	Economics of operating/buying/selling/leasing resource networks	Policies relating to multiple vehicle use (i.e., local airport noise policies)
γ	Resources in a transport sector (e.g., air transportation)	Operating collection of resource networks (e.g., commercial air Ops)	Economics of a business sector (e.g., airline industry)	Policies relating to sectors using multiple vehicles (FAA certification, safety, etc)
δ	Multiple, interwoven sectors (resources for a national transportation system)	Operations of Multiple Business Sectors (i.e., operators of total national transportation system)	Economics of total national transportation system (All Transportation companies)	Policies relating national transportation policy
ϵ	Global transportation system	Global operations in the world transportation system	Global economics of the world transportation system	Global policies relating to the world transportation system

The main idea of DeLaurentis is lack of a field of study or process to answer decision makers problems of System of systems type in a systematically manner.(DeLaurentis and Callaway 2004) He introduces his hierarchical view of SoS problems.

3.1 SoS Characteristics category

SoS characteristics that mentioned and discussed in previous chapter can be divided to two categories of Managerial and Physical. As it depicted in Figure 3-2, some characteristics like independency, leadership and self organizing are categorized in the “SoS of” or operational and managerial and others like interrelationship, emergence and evolutionary put in “SoS About” or structural and functional column.

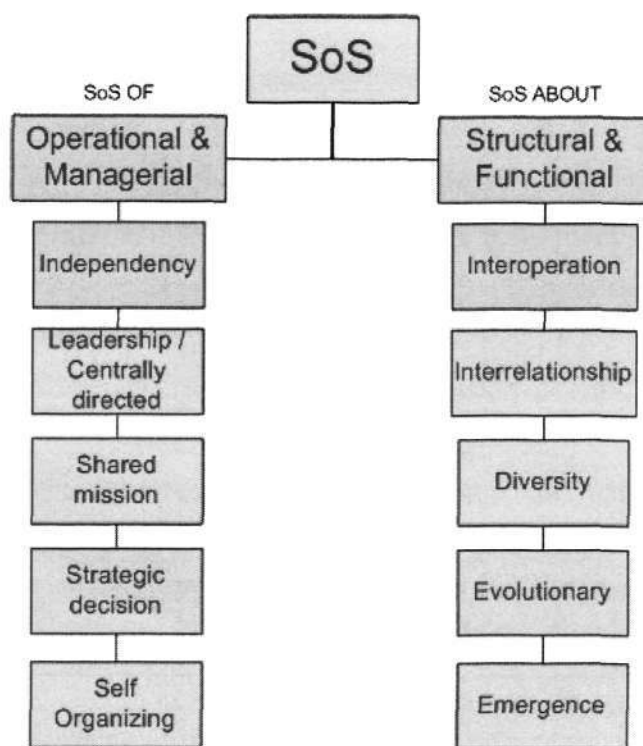


Figure 3-2 SoS characteristics categories

This categorization is useful in very big complex enterprises to better understanding SoS features and criteria.

Chapter 4 SOME SoS APPLICATIONS

In this chapter for better understanding of SoS, some of the applications are presented as follow:

4.1 SoS in Interoperable communication

This project aimed to make public safety and public services more efficient. It is one of the US homeland Security projects. (*Safecom 2008*) It is designed to help the emergency response community, as well as local, state, and Federal policy makers, to understand the System of systems concept, the benefits of applying this concept, and how it can aid agencies in achieving interoperability. SoS is defined as: “Group of independently operating systems—comprised of people, technology, and organizations—are connected, enabling emergency responders to effectively support day-to-day operations, planned events, or major incidents.”

In this scenario, component systems are interdependently related within and across all lanes of the Interoperability Continuum (governance, standard operating procedures, technology, training and exercises, and usage). Figure 4-1 shows Compatible technology between jurisdictions alone will not make an agency interoperable; the jurisdictions must connect technology, people, and organizations to achieve interoperability. It is to increase a local agency’s ability to own and manage an independent system while collaborating with other local, regional and state systems. Figure 4-2 shows local, regional, state, and interstate System of systems expansion and collaboration. Communities must consider the demographic and topographic differences of neighboring jurisdictions as they connect or share systems functions across their own boundaries.

Communication improves as agencies, large and small, join together to interoperate. No single solution exists to connect independent systems but standard interfaces can aid in integrating previously incompatible equipment. Connecting systems with standard interfaces has the following operational, technological, and economic advantages over connecting systems using proprietary interfaces:

- Increased Operational Benefits – As standard systems and subscriber devices proliferate, emergency responders can respond anywhere, bring their own equipment, and operate on any network immediately, when authorized.
- Increased Capability – Systems based on standards can connect to other systems without compromising functionality.
- Increased Efficiency – The need for additional equipment and technical resources to improve interoperability decreases.
- Increased Flexibility to Upgrade – Each system can make changes or adopt new technology without affecting other connected, standards-based systems.
- Decreased Reliance on Proprietary Technology – Jurisdictions can choose from multiple vendors.
- Decreased Cost – Price competition increases and the need for expensive customized interoperability solutions is reduced. Training can be standardized across jurisdictions, thus reducing training costs.
- Increased Capacity to Expand – Standards-based solutions are more likely than proprietary solutions to be able to integrate the next system into the larger System of systems.

Whether or not standards exist or are available, a System of systems approach supports each agency's ability to think outside its jurisdictional

boundaries. Each agency can see itself as a component in a regional and nationwide System of systems connected through compatible equipment as well as collaborative approaches toward a common goal.

Case example: Airplane crashes

It is an example of the lack of communication interoperability occurred in Jan 1982. Air Florida Flight 90 crashed during take-off from National Airport in Washington, D.C. The plane hit the 14th Street Bridge and plunged into the Potomac River kills 78 people. Because of its Special location multiple local, state and federal emergency responders were dispatched to crash site, but different emergency responders were unable to communicate with each other because of using non-standard frequency.

Last and the best experience of Using SoS in Interoperable communication happened in Jan 2009. A US Airways jetliner has crash-landed in the Hudson River just after takeoff at LaGuardia. Of course the courage of the pilot “Chesley Sullenberger” was praiseworthy, but beside that, it took only 3 minutes to first ferry arrived to rescue passengers. All 155 passengers and crew were rescued safely. All emergency responders be in the incident are very soon and communication done well.

4.2 US Coast Guard Integrated Deepwater System program (2001)

The Coast Guard's Integrated Deepwater System (IDS) is a critical multi-year program to modernize and replace the Coast Guard's aging ships and aircraft, and improve command and control and logistics systems. It is the largest acquisition in the history of the Coast Guard.(CGIDSP 2001)

A critical element of this program will be the modernization of C4ISR (command, control, communications, computers, intelligence, surveillance and reconnaissance) systems. The total package that is a C4ISR "System of systems" Enterprise to be delivered to the U.S. Coast Guard and its Deepwater cutters, aircraft and shore facilities establishes common software, systems and components across all surface, air and shore assets. Simply put, this system provides interoperability, improved situational awareness and new levels of Maritime Domain Awareness (MDA). Figure 4-3 ICGS SoS Interoperability

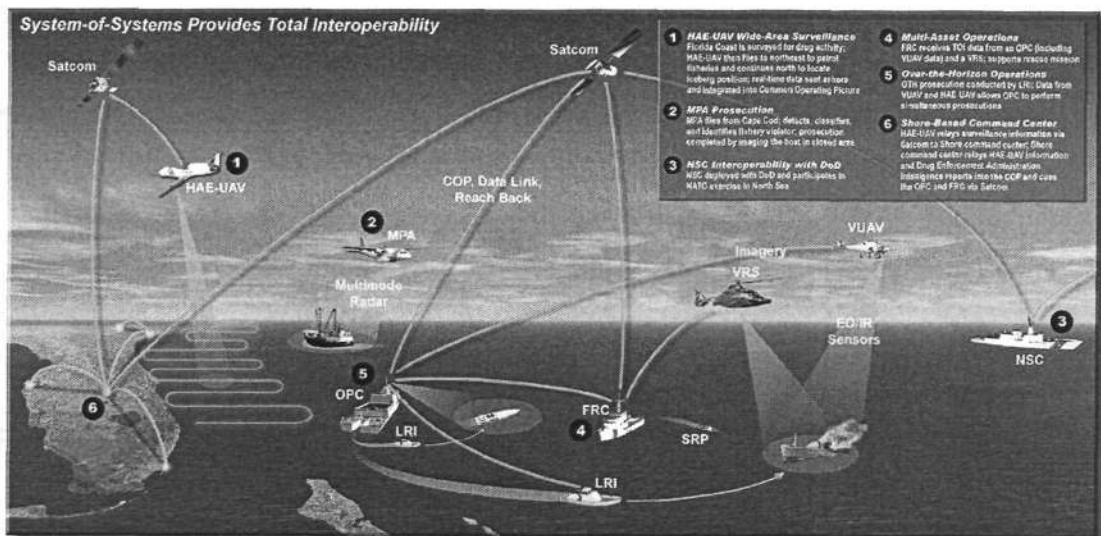


Figure 4-3 ICGS SoS Interoperability (CGIDSP 2001)

4.3 Air Traffic Management System

Moving people and goods efficiently and most importantly safely are the top priorities of air transportation. The aim was to design a system to ensure safe separation of aircrafts in the sky. This task has become increasingly more complicated over the years. Air traffic management system is a worldwide connecting system that is able to handle more aircraft at the same time. For instance only in 2008 in United State alone more than 650 million people used air travel to reach a destination and about 10 million planes departed from the airports across the US. Better routes, improved situational awareness, and more on time arrivals are the main objectives of this System of systems. (Figure 4-4) Scientists are working to give feedbacks of this SoS to aircraft industries regarding the passengers travelling demand in different routes. Future aircrafts size and capacity could be optimized via this information.



Figure 4-4 Air Traffic Management System (Changi 2009)

4.4 European airspace Integration (SoS Civil Project)

The European Air Traffic control Harmonization and Integration Program (EATCHIP) is a major project being undertaken by Eurocontrol (the European Organization for Safety and Air Navigation). The primary objective of this program is the integration and harmonization of existing Air Traffic Control systems (ATC) and procedures within the Europe and after that, the development of a Joint European Air Traffic Management System (EATMS).

Air traffic increases day by day. To have more traffic capacity in the same air space, need a very precise data for aircraft during take-off, flight and landing. EATMS is a real time safety critical system that will be able to give precise data for aircraft. During the flight, aircraft will have the ability for precise navigation and thus ATC will be able to give aircraft shorter and more economical routes depending on the traffic.

Airspace consists of Flight Information Services (FIR) sectors over which an Area Control Centre is responsible for controlling all the flights. The FIR is divided into sectors, which are defined according to the range of the radar that is responsible for that section. The Joint EATMS aims to automatically hand over the responsibility of an aircraft, between the controllers of sectors and FIRs, something that now is achieved manually over the radio. (Despotou, Alexander et al. 2003)

The joint EATMS satisfied most of the SoS characteristics and can be a good model of SoS. In this project all control stations have to communicate with each other to be able to make the automated handover of an aircraft's responsibility. Data needs to be shared across the whole system in order to predict any conflicts between flight routes. To share data EATMS use On Line Data Interchange Protocol (OLDI). This simultaneously sharing of data make the system complicated.

Moreover, complexity and the excess of different and independently developed systems involved is indicated by the different systems that participate such as Aeronautical Telecommunications Networks (ATNs), user interfaces (radar screens etc.), radar stations, databases (Oracle, DB2 as well as an OO database sitting on top of CORBA are considered). Each sector controller has to make decisions about the aircraft in its responsibility and it is Decentralised control or autonomy of the system.

(Wortman 1998) brings the dynamic reconfigurable characteristics of JEATMS. During night time with dramatically reduced traffic, a given set of sectors will be joined to one big sector (sector collapse) and during peaks of traffic load sectors may be split in smaller unities (sector decollapse)

In terms of dependability, JEATMS is safety critical and based on real time accurate computation of aircraft trajectories. It has maximum availability and minimum maintenance time.

4.5 New York City Yellow cab System

(Consulting 2006) New York City (NYC) Yellow cab System of systems consists of 13000 licensed medallion taxicabs. It serves 240 million passengers a year which creates a US\$1.82 billion industry. Statistics shows Manhattan residents hail a cab 100 times a year. The taxicabs are privately operated by independent companies or individuals. At the same time they are closely regulated by New York City Taxi and Limousine Commission (TLC). NYC yellow cabs operate predominantly on a street hail basis and do not operate on a dispatch basis.

Using five SoS characteristics stated by (Boardman 2006) the NYC Yellow Cab System of systems have been analyzed.

Autonomy: all Yellow Cabs operated by independent entities and make their own decisions on how to operate. But they should have conformity with TLC that set the regulations such as taxi fares, safety inspections, and issue licenses. The other opposing factor to autonomy of Yellow cabs is independence aspect of operating the taxi cab. According to the survey done by (Consulting 2006) independence is more important than making money for the taxi drivers.

Belonging: all NYC Yellow Cabs have a share mission to serve NYC customers in a safe, efficient and affordable manner. The opposing forces here for belonging is all the cabs regulated by one single agency as a centralized body named TCL. TCL sets the overall transportation policy governing cab services, in the other hand taxicabs are privately operated. Lack of a central dispatcher make the system decentralized. They provide transportation exclusively via street hails or cab stands.

Connectivity: New York City Yellow Cabs are connected through the physical transportation network and social networks. Roads, bridges, gas stations, parking lots and repair shops as physical and traffic news reports, tips where the most customers are the social networks. In such a strong net centric structure each driver pursues his/her own interests(Consulting 2006). There are two opposing forces here to connectivity of Yellow cabs. First, with all of this information and networks there is a competition among the yellow cab drivers for customers because mostly they are on hail base. Second, each Yellow Cab within the SoS is a whole on its own because they individually follow their own success criteria.

Diversity: cars, drivers, operators make diversity in NYC Yellow cab SoS. Different cars i.e. hybrid, van, SUV, old, new together with different drivers in ideas ethnicity, age, background make this SoS more complicated. In contradiction homogeneous cause by TCL rules like yellow color for all, driving and safety license requirement playing as opposing factor to diversity characteristic of this SoS.

Emergence: all systems are emergent and can be classified as intended and unintended. Safety, comfortably and efficiently transport of NYC passengers is the main intended emergent property of Yellow cabs that is achievable by collaboration of all of them. Although removal of one cab will not change the overall performance of the SoS.

Chapter 5 DEVELOPMENT OF A SoS FRAMEWORK

The SoS definition used in this research is based on (Crossley 2004)'s . A System of systems is comprised of individual systems capable of independent operation. Using multiple systems in collaboration can provide capabilities well beyond those available from a single system. Further, the ability for each constituent¹ system to operate independently can provide increased robustness for the overall System of systems. However, these aspects provide an additional level of complexity in determining which systems provide which contributions to the overall performance.

System of systems includes management and organizational aspects as well as technical aspects. This proposed SoS framework could apply on any large scale complex project, organization or program to evaluate potential of being a SoS and then manage it to achieve its goal more efficiently. The novelty is to cover both technical side that is to include systems engineering and management aspects.

The concept of System of systems is wide enough to implement in any areas and achieve its benefits of efficiency on quality, time and cost. The sequences of this framework are:

- SoS diagnosis, including identify characteristics and discriminators
- SoS determination and analysis, to clear deviations and opposing factors to an ideal SoS and defining related attributes

¹ The term constituent refer to autonomous components of a system of systems. Sometimes constituents systems are organizations or individuals, that will be refer as stakeholders.

- SoS Hierarchical assessment, in different levels and categories.
- SoS implementation, apply the model to existing system or put it in the plan to design a new system and calculate the SoS compatibility factor.

All of mentioned sequences will be described in this chapter.

There are some important points regarding context of System of systems that should be considered:

- A SoS constituents vary in types. They are not just hardware and software. Organizations, hardware, software and people are interacting with each other and their influences should be considered.
- All the constituent systems follow the main goal of SoS. Even if some individual constituent system seem different but they belong to SoS and play a role to achieve the overall purpose.
- A SoS should be adaptable on changing technologies, customer needs, environment, economy and policy.
- In some cases a System of systems operates within specific cultural, political, economical and legal environment. In such cases, study of all mentioned parameters even ethical influences is necessary.

5.1 Definitive SoS Characteristics and Attributes Related to Critical Infrastructures

The most important part of this model is defining characteristics and attributes related to SoS that is going to be analyzed. The multiple constituent systems involved in a System of systems will have different perspectives on technology, organizational relationships, commitments and other factors. Interoperation and evolutionary developments are the key components in a System of systems context that should manage with a diverse set of stakeholders within the SoS. Knowing more details about SoS environment helps to predict some unwanted happenings and prevent leading the SoS to chaos. This analysis could be more accurate if an SoS expert team leads various stakeholders associated with the specific System of systems in discussion sessions and workshops.

The SoS characteristics used for this research are as follow:

Autonomous

Constituent systems develop and operate independently from each other in a large degree, but contribute to the overall evolution of the System of systems. Sometimes independency of constituents is the result of the distinct acquisition and management authorities for the constituents.

Each constituent system has its own managerial and operational independence. Case by case it may have different meanings. For example in military domain and simultaneous attack of UAV missiles, each UAV has its own operation and managing its own plan and target. In enterprise domain each organization has its own managerial and operational team and independency. In some cases master plans may affect managerial issues but it is in convergence of purposes.

Core leadership

In a SoS environment the core mission defined to monitor and harmonize each constituent system's mission to follow the predefined whole SoS mission. Coordination of functions via communications between constituent systems affects the rate of operations, and activity initiations. As shown in (Figure 5-1) the core part that named "Lead System Integrator" has the responsibility to do the described activities. As all of the critical infrastructures are in class of directed SoS, a core leadership is essential. Attributes like information/knowledge management, net-centric issues, and Coordination of functions can be derived from these characteristics.

Convergence in purpose

Contribution of each constituent system to the overall evolution of SoS is the key role of each constituent. It is why it is selected as a part of whole. It is supposed not to do the same work in parallel the constituents. In some cases it may mean centralizing network of commands, but it can be decentralized with a common purpose in all the parts.

Evolutionary

A SoS should be alive. Dynamic changes within the SoS as one of the most important SoS discriminators, include the technological, cultural, environmental, political, economical and customer needs monitoring and improvement. Evolutionary development could be the most important characteristic of any SoS that brings benefit of SoS thinking.

Diversity

The systems that comprise an SoS are diverse. Each constituent system is likely motivated by a certain set of needs, which tends to change over time. Changing stakeholder needs for the systems within an SoS will likely lead to different evolutionary path, since each constituent system is likely to be managed separately, with separate budgetary constraints, political issues, etc. SoS is challenging with environmental diversity also.

Interoperation

Communication between constituent systems in a SoS is one of the interoperation tools that helps each constituent systems to follow the main purpose. Interoperation is an essential characteristic and it should establish as an infrastructure in the context of SoS.

To analyze a System of systems by mentioned characteristics it is essential to break down the characteristics to their basic components, fourteen attributes are applied. This break-down of attributes is depicted in the Table 5-1. Description of characteristics and attributes of SoS framework defined through three main views of systems engineering naming, the physical, functional and operational views. These 14 attributes will be analyzed to measure the SoS compatibility of the systems.

Table 5-1 SoS intellectual Model characteristics & Discriminators

Characteristics	Description	Attributes
1-Autonomous	Integration strategy Independency Own mission	1-Operational independence 2-Managerial independence 3-Own business process and Own budget
2-Core leadership	Coordination Cooperation Network centric	4-Information/Knowledge management 5-Net centric issues 6-Coordination of functions
3-Convergence in purpose	Joint mission Sense of belongings	7-Avoid of concurrent Activities 8-Interrelationship and connectivity 9-Have a joint mission
4-Evolutionary	Dynamic change Emergent behavior Adaptive environment	10-Evolutionary development 11-Dynamic Capabilities
5-Diversity	Environment diversity Customer need diversity	12-Heterogeneous constituent systems 13-Mix of existing and New systems
6-Interoperation	Synergism	14-Interoperability of constituent systems

To evaluate a system SoS compatibility there are three levels of Low, Moderate and High. As shown in Table 5-2 grading systems that use for this purpose is based on numbers: (1) indicates the Low attendance of the characteristics, (2) moderate and (3) indicate High or strong compatibility to SoS characteristics and attributes. These numbers are only indicative for illustration purpose. Grading the attributes is based on evidences from organization annual reports, websites, etc.

Table 5-2 SoS compatibility measurement

Attribute \ Status	SoS measurement		
	Low 1	Moderate 2	High 3
1. Autonomous			
1-Operational independence	Operational procedures related to other systems in the same or higher level	Using the higher level operational procedure beside issuing by their own system	Operational of each constituent system is completely independence to others
2-Managerial independence	Share management rules or even people to take the business related decisions	Using the guide and ideas of others as a lead but have its own management	Management independency to other related systems
3-Own business process and Own budgets	Injecting all budget and process form a higher level	These systems need support but they have their own budget also	Responsible to its own business, budget and process
2. Core leadership			
4-Information /Knowledge management	Information and documentation is not stored centrally to give the idea of experiences to other systems	Partially information management and care about knowledge management	Centralize its management and information sharing for better arrangement and effectiveness
5-Net centric issues/planning and process development	SoS and constituent systems have not a Synchronized development planning	Responsibility of each constituents system to do its own, beside existence of a master plan in the SoS	A centralized-synchronized development plan working as a master plan, top-down
6-Coordination of functions	Each constituent systems working separately that makes some conflicts	Coordination between some of the constituent systems but not all	Well defined coordination procedure for each constituent systems

Attribute \ Status	SoS measurement		
	Low 1	Moderate 2	High 3
3. Convergence in purpose			
7-Avoid of concurrent activities	Lack of strategic plan and decisions to prevent concurrent jobs	Existence of monitoring but lack of power, because of each constituent system profit	A powerful control and monitoring due to (eg. 3 monthly reports) of each constituent systems to prevent concurrent jobs
8-Connectivity	Loosely connected business/operational relations between constituent systems	Collaboratively integrated business structure between constituent systems based on linked functions of system	Built-in integrated corporate relationship between constituent systems in plan
9-Have a joint mission	Different constituent systems working separately for their own goal and partially to the SoS mission (different priority)	Due to problems some of the constituent systems do not spend all their resources to SoS main mission	Existence of each constituent system related to doing its mission to satisfy the SoS target
4. Evolutionary			
10-Evolutionary development	Study of history of the system shows very rare development in constituent systems level	Staged development can be observed both SoS and constituent systems level	Having a long term plan for evolutionary development, study of history of the system present it
11-Dynamic Capabilities	A rigid SoS structure, almost fail to dynamic changes in terms of profit	Potential of changing in constituent systems are available, but not active. with no master plan	Ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments

Chapter 5: DEVELOPMENT OF A SoS FRAMEWORK

Attribute \ Status	SoS measurement		
	Low 1	Moderate 2	High 3
5.Diversity			
12-Heterogeneous constituent systems	Systems Doing similar in terms of functions and operations	A mix of different but not complete functional systems Operating together	Collaborating wide divers systems different in structures to reach the main goal of whole SoS
13-Mix of existing and New systems	Systems is rigid to add new or upgrade old existing constituent systems	Diversity in constituent systems with different ages	A good mix of new and existing systems with the potential of accepting new systems
6.Interoperation			
14-Interoperability of constituent systems	Exist of constraint in constituent systems to have interoperable connections	Existence of interoperability between constituent systems only for special circumstances	Interoperability between all constituent systems to increase effectiveness

The overall degree of SoS compatibility can be measured by the sum of all fourteen attributes graded for a candidate SoS. Weakness of any of these attributes can decrease the overall SoS compatibility score. Low or moderate attributes should be analyzed for their causes of the lack of compatibility. This job should be done by the analysts that have comprehensive domain knowledge about the relevant SoS domain areas. Use of historical statistical data, interviews with relevant management, study of master plans and conducting surveys are some of the useful tools in determining the SoS compatibility.

Mostly a system with a good score in this analysis should be a system with a very good management that implements a powerful master plan based on the System of systems attributes. Benefits of SoS characteristics like Interoperability, evolutionary and incremental development can be evaluated by

effectiveness, good Return On Investment (ROI) and time efficiency of the whole system.

5.2 SoS Hierarchy and categories analysis

A SoS consist of a large number of viable subsystems that are considered as the constituent systems in this study. Each constituent system has its own behavior (activity), mission, resource and viability management besides its functions. In a SoS environment the core mission is defined to monitor and harmonize each constituent system mission to follow the predefined whole SoS mission. Coordination of functions via communications between constituent systems affects the rate of operations, and activity initiations. Figure 5-1 Figure 5-1 SoS shows SoS functions as a function of the whole include mission and behavior harmonization of the constituent systems, and interchange harmonization to enhance cooperation, coordination, compatibility and synergy. (Hitchins 2007)

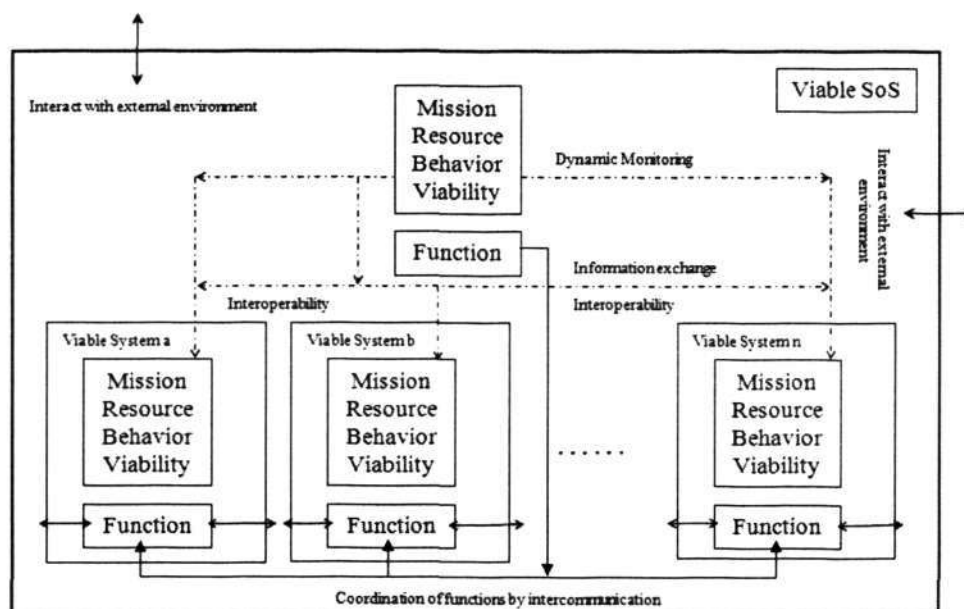


Figure 5-1 SoS Interconnection diagram (adapted from Hitchins 2007)

As shown in Figure 5-2 the SoS hierarchy view in this research is synthesizing the systems engineering approach in different layers of lexicon presented by DeLaurentis (DeLaurentis and Callaway 2004; Popper, Banks et al. 2004) in the article titled “ A System of systems perspective for public policy decisions” and considered in System of systems Symposium: Report on a Summer Conversation.(Popper, Banks et al. 2004)

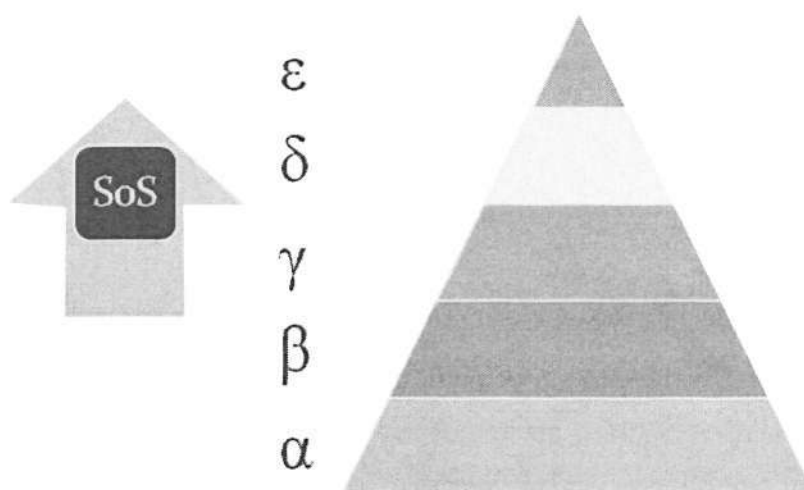


Figure 5-2 SoS in analysis of Large scale projects

SoS characteristics are stronger in higher levels. In lower levels system engineering models and approach are dominant. The main concept of SoS, because of its inherent managerial characteristic has a hierarchical, holistic top-down approach.

Chapter 6 SoS FRAMEWORK VALIDATION

6.1 Introduction

National transportation system (NTS) of Singapore as a modern transportation system is the case study to validate the SoS framework for this research. There are so many factors that make it more complex. There are several factors that play important role in the concept of sustainable cities encompassing economic, environmental, social and political. SoS in NTS level involves all of these factors to make Singapore's sustainable national development. Viability of such a system is a wish always for city planner and decision makers. A viable system is one that is able to exist, survive and operate in a suitable environment, acquiring its own resources, performing its functions and, as an open system, maintaining dynamic equilibrium.

Infrastructure investments tend to be lumpy, and usually decisions made by governments in consultation with private sector or international agencies. Good examples of these huge project investments in Singapore include Changi airport and more recently terminal 3, MRT existing and future lines and container ship terminals. These projects contribute a big role to the economic development of Singapore and to the region around. Infrastructure provision and economic growth has been the subject of extensive discussion during the last decade (Banister and Berechman 2000). The case of Singapore is very interesting because of its government's attention during last 40 years, more than other parts of the world, in: sustainability, major public investments, structuring the context for private activity and international competitiveness (Willoughby 2001). One of the most important strategic infrastructural investments by Singapore government is the Changi International Airport Complex. In the following section progress of the staged strategic decisions will be explained.

Study of Mercer (2009) survey about Quality of living and City Infrastructures shows interesting results for Singapore's position in 2009. Mercer evaluates local living conditions in all the 420 cities it surveyed

worldwide. Living conditions are analyzed according to 39 factors, grouped in 10 categories. Statistics shows Singapore ranked first (Figure 6-1) in Infrastructure and 26th in quality of living (Figure 6-2).

City infrastructure			
Rank 2009	City	Country	Index* 2009
1	SINGAPORE	SINGAPORE	109.1
12	TOKYO	JAPAN	103.4
49	SEATTLE, WA	UNITED STATES	96.5

Figure 6-1 Mercer Survey, City Infrastructure 2009 (MERCER 2009)

Quality of Living					
Rank 2009	Rank 2008	City	Country	Index 2009	Index 2008
1	2	VIENNA	AUSTRIA	108.6	107.9
26	32	SINGAPORE	SINGAPORE	103.5	102.9
50	50	SEATTLE, WA	UNITED STATES	99.8	99.8

Figure 6-2 Mercer Survey, Quality of Living 2009 (MERCER 2009)

Considering the national transportation system as SoS is especially challenging when considering the options for an “on demand” transportation service. The term “on demand” used here means that transportation industries should get feedback on customer growth. On other hand, the trend of manufacturing in type and passenger capacity of aircrafts should be considered in response to travelling demand of region. Putting together a national plan is a daunting task, and there is a clear need for better support for informing this sort of policy. (Popper, Bankes et al. 2004)

First it should be proved that Singapore NTS fits into a SoS model. NTS consists of many constituent systems with a non-hierarchical order that makes it a complex distributed system. Study and analyses of each constituent could be a good research topic that needs more time to do. In this research with a top-

down holistic view of Singapore NTS in general and Changi Airport in particular considered as a case study.

Planning Singapore's National Transportation System is the main responsibility of the Ministry of Transport (MOT). The main focus of the ministry is to bring about efficient and cost-effective transportation to enhance Singapore economic competitiveness and quality of life. Transportation of goods and people in an efficient time and cost, normally is the main goal of any NTSs. (MOT 2009)

MOT oversees the development and regulations of civil aviation and air transport, Maritime and seaport and Land transport. Through the Acts of Singapore parliament, four statutory boards were established as follow:

- The Civil Aviation Authority of Singapore (CAAS)
- The Land Transport Authority (LTA)
- The Maritime and Port Authority of Singapore (MPA)
- The Public Transport Council (PTC)

The MOT vision is to make Singapore a global hub in aviation and maritime transportation.

This research aims to validate the model developed in Chapter five using the Changi International Airport as a main integral part of Singapore NTS. For a better understanding of situation Figure 6-3 Singapore NTS, SoS depicted. It is just an integrated part of this larger System of systems to show the key characteristics and their interrelationship. This diagram depicts different layers of NTS SoS mentioned in DeLaurentis's (2004) lexicon model. Evolutionary, Emergent behavior, interoperability, Synergy, Joint mission and Autonomy of constituent systems are some of the SoS characteristics that could be deducted.

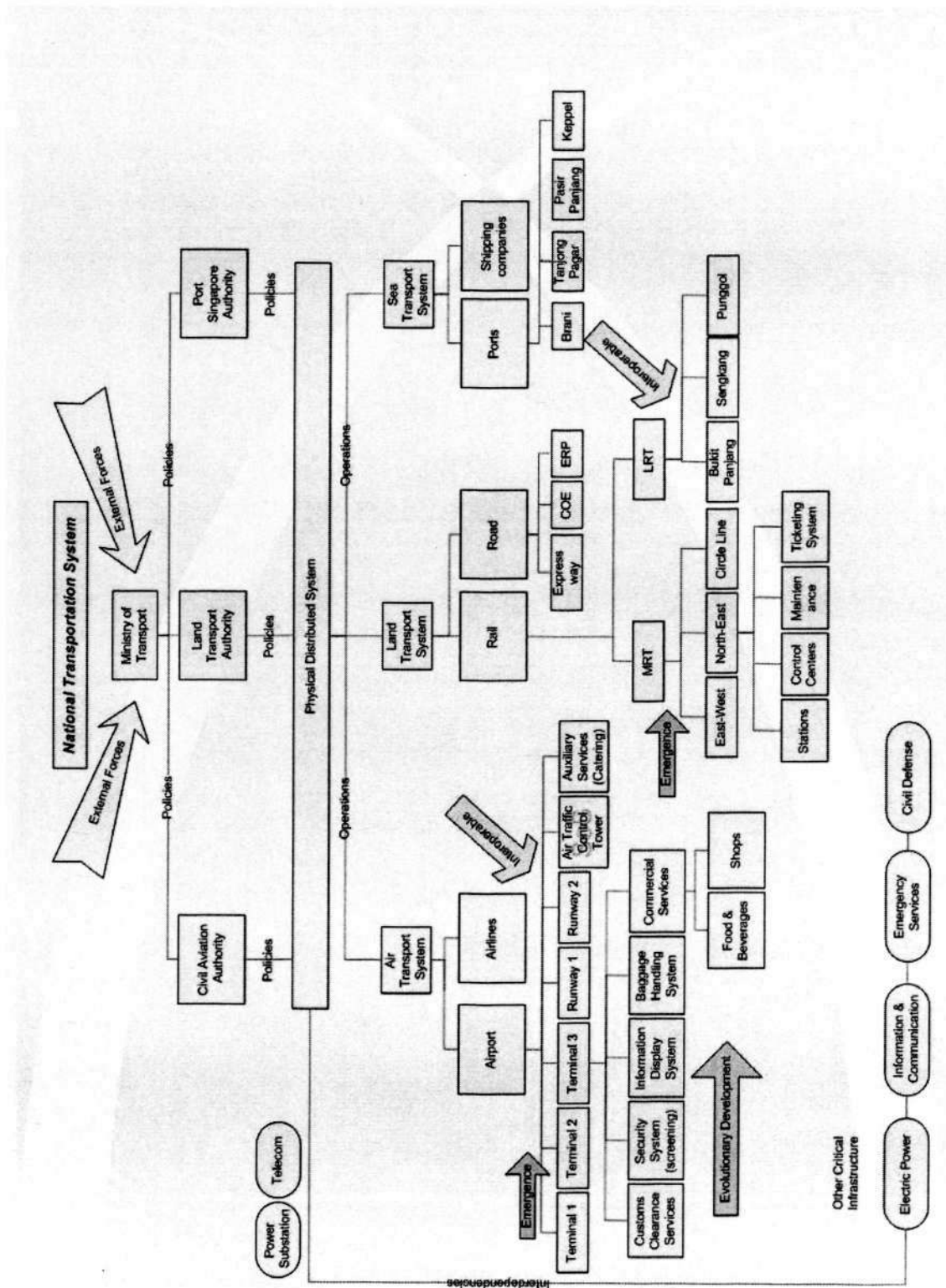


Figure 6-3 Singapore NTS, SoS Compatibility

6.2 A CASE OF CHANGI INTERNATIONAL AIRPORT

Background

Singapore has a population of 4.9 million people and a land area of 710 km². It was a British trading colony from 1819. It joined the Malaysian Federation in 1963 but two years later became an independent country. Singapore subsequently became one of the world's most prosperous countries with strong international trading links.

In 1975 the decision of relocating Singapore international airport from Paya Lebar to Changi was made by the then Prime Minister Mr Lee Kuan Yew. Following this decision, two teams were formed to study airports around the world and in parallel a master plan was drawn up by the Public Works Department (PWD). Changi is located in eastern part of Singapore and Paya Lebar is situated about 9 km to the west of Changi. Paya Lebar is located near a densely populated area and bounded on the west by Serangoon River. Rapidly growing of air traffic made government to re-think about expansion of Paya Lebar or consider building a new airport at Chnagi. Mr. Goh K.C. (one of the special committee members on assessment of these two options) proposed several reasons that proved the establishment of Changi airport is a better decision. These reasons also presented in an International Symposium on airport planning and development as follow(Goh 1982): Better road access, No interruption to air traffic movements at Paya Lebar Airport while Changi was under construction, Less residential areas affected by air and noise pollution, Better airport approach via the sea than Paya Lebar Airport where aircrafts had to fly over city areas, Less hazards and Paya Lebar option also entailed sterilization of large tracts of economically useful lands because of the height control on buildings near the airport.

The above factors of environmental constraints, accessibility and economic development benefits besides land use that is the most critical one, convinced Singapore government in 1975, to convert the existing military airport at

Changi into a new civilian airport instead of building a second runway at the Paya Lebar Airport(Phang 2003).

Prime Minister Mr. Lee Kuan Yew mentioned in his book (Lee 2000):

“It was the best S\$1.5 billion investment we ever made.”

In 1981 Changi airport terminal one (T1) began operations with a capacity of 12 million passenger movements per annum. Its land, partly reclaimed from the sea. The airport has become famous for its policy of investment in infrastructure capacity ahead of demand. The strategy of providing capacity ahead of demand has consistently guided Changi in maintaining the highest standards of services, safety, efficiency and comfort. The Civil Aviation Authority of Singapore (CAAS) in 1988 commissioned the International Civil Aviation Organisation (ICAO) to develop a forecast on aviation activity for a period up to 2015. Using trend analysis, simple econometric models and expert judgment techniques the study predicted accelerated passenger growth of between 5.7 percent and 7.2 percent per year for the period 1990-2015(Lim 2008). So by 2015, Changi is supposed to accommodate 70 million passengers annually.

Three years later, in 1984, government approved the construction of terminal two (T2), as terminal T1 was not able to cope to predicted demand. In 1990 construction of T2 was completed which doubled the passenger handling capacity of Changi Airport. Competitors like Hong Kong international Airport and Kuala Lumpur International Airport, also expanded their capacity parallel with Changi development. The construction of terminal three (T3) started in 2000 and celebrated its opening in Jan 2008. The passenger capacity of Changi reached 64 million passengers per annual. Beside the three main terminals, a budget terminal was built to service the Low Cost Carrier (LCC) airlines. Budget terminal play an important role in Changi competitiveness in the region.

Study of Changi Airport history shows an evolutionary success and growth within 35 years of good management and efforts. It is certainly a good example of Singapore's infrastructure development using, management and technology. It helps to evaluate and validate benefits of SoS perspective. These days operating an airport has changed to a complex enterprise. Safety, continual improvement, innovation and excellence in all aspect of businesses, create sustainable values for airport stakeholders.

In management analysis of Changi airport, managers have to integrate multi-level objectives all together. Management has to take a global view of coordinating and integrating all functions in different layers of system and subsystems to work together as a whole. But it does not mean to take the autonomy of its constituent systems. The management philosophy takes a holistic approach towards coordinating the interests of government agencies, airport concessionaires, tenants, suppliers, and passengers that are the most important element. It shows the interoperability characteristic of Changi airport. The aim of management is to serve customers including: passengers, greeters, well-wishers and casual visitors to the airport in an efficient and respectful manner.

The Civil Aviation Authority of Singapore (CAAS) continuously strives to keep the airport at the leading edge of technology and customer service. Patriarchal role of CAAS is against the autonomous of each of the constituent systems of Changi airport. When it receives a complaint against any agency, airline, tenant or supplier, it will not hesitate to take action.

Changes in the aviation and construction industries along with the emerging opportunities in airport retailing took place rapidly during last 20 years. These diverse industries, with quite different global opportunities, at different stages of evolution, political challenges, environment implications and financial risks need a team of experts to monitor and navigate dynamically to adapt. CAAS's main job is to make the best short-term and long-term strategic decisions to make Singapore Changi Airport an aviation hub in this region.

Air traffic has been growing considerably over last 30 years, and expected growth to continue in to the future. As the result, there is demand for new big airports to be built. By developing Changi, because of Singapore geographical location at the crossroad of major air routes, it assumed its proper place to become an international aviation hub.

CHANGI Airport SoS General Structure

In July 2009, follow the policy of corporatisation of governmental authorities, managerial and operational activities related to Changi Airport were transferred to Changi Airport Group while regulatory functions remained with CAAS. The main philosophy of such privatization is to leverage on the autonomy that has been given to the airport company to innovate in the operations and management of Changi Airport. As it depicted in Figure 6-4, CAAS will focus on long-term strategic plans to make Singapore as a successful air hub in this region and Changi Airport Group, through innovation in management and operations, will try to make Changi the world's leading airport.

Air traffic control, baggage handling system and security and detection system are just three of the many complex constituent systems of Airport SoS. These are complex large-scale systems working together, connected to each other to meet a bigger challenge. In our case, the challenge is "to provide efficient and effective services to airport clients in a competitive environment". In SoS, functional sub-systems work at a lower hierarchical level (Figure 6-4). They are in α level of SoS lexicon (DeLaurentis 2005) . In this level systems Engineering tools and knowledge can solve most of the problems.

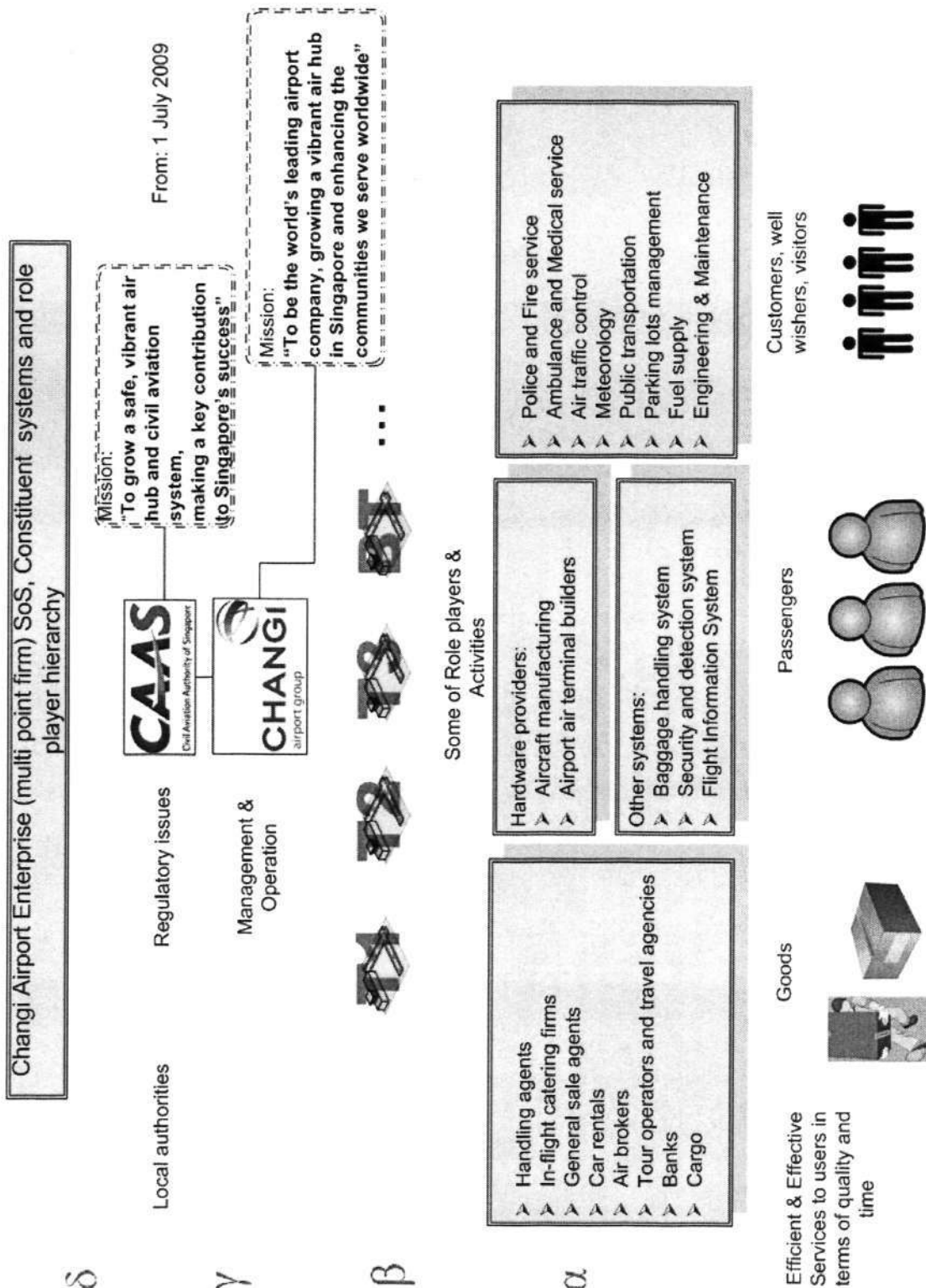


Figure 6-4 Changi Airport General SoS Structure

Master Plan of the CHANGI Airport SoS

The ultimate goal of the Changi Master Plan is to ensure that the new facilities and systems continue to improve the quality of service level at Changi. CAAS planners and airport managers with a team of consultants worked on the master plan. Changi's infrastructure is the main focus of the master plan to accommodate future growth competitively.

The other main focuses in the master plan are as follow: improved visibility of all aircrafts form the control tower, dual taxiways, good locations for ground service equipment, reduction of road/taxiway intersections, good airside and landside access roads, creating more commercial opportunities, better peak hour spreading and the efficient use of automation.(Lim 2008)

The other important characteristic of the master plan is its dynamic monitoring of key operational elements to react quickly in case of volatile operational conditions. All trends and logs collected to provide a database to help future decisions and policies to predict future air transport demands in the region considering Singapore as a main hub. Also infrastructure's and facility's maintenance and development is one of the most important criteria in Singapore. In the master plan, the current facilities of T1 and T2 were reviewed to find any possible way of increasing their capacities in terms of adopting new technologies or efficient passenger processing systems.

Competitiveness of Singapore Changi Airport is one of the other important factors in the master plan. In writing the master plan Porter's five force theory applied to the aviation industry had been used.(Button 1997; Williams 2006)

- ✓ Increasing globalization and adaptation to the process of convergence
- ✓ Increasing regionalization brought about by the increasing stress on location as a comparative advantage
- ✓ Economic incentive for consolidation in order to obtain economics of scale through alliances and networking

- ✓ The relative speed of market liberalization, which is now driving some of the important economies in the region under review
- ✓ The need to remove current limitations on market competition, in order to allow airlines and airports to take full advantage of the increasing internationalization of economic activities such as tourism.

Park (2003) defined five core factors as basic preconditions to analyze airport competitive strength. These five core factors are as follow:

- Spatial factors: The level of development around the airport, such as international trade zones, logistics and convention centers, aviation-related industrial complexes and other facilities.
- Facility factors: The level of airport facilities and expandability of these facilities at existing airports to increase capacity.
- Demand factors: The level of origin-destination (O-D) demand and the density of transit and transfer traffic volumes for hub and spoke network development.
- Service factors: The level of services to users, types of airport operations, and airport charges.
- Managerial factors: Economic considerations such as airport operating cost, productivity, and revenue structure.

Park's analysis defined the new Hong Kong International Airport as the most competitive in Northeast and Southeast; Singapore Changi Airport and Seoul Incheon were placed second and third. (Park 2003)

Systems Engineering in Heart of SoS

A multitude of systems are working in Changi Airport to achieve Changi's main goal to provide excellent services to passengers, well wishers and customers. Adopting the lexicon model to Changi Airport found that most of these systems are working at α level that can be modeled and studied as a Systems Engineering (SE) models. Changi Airport as a SoS is managed and operated with SE approach at α level. For instance, Flight Information System, Baggage Handling System and Security and Detection System are three good examples of SoS component systems working in α level of the SoS. Also bigger complex systems like Air Cargo work as a part of global goods transportation as one of the important constituents systems of Changi Airport. BHS as a α -case component system is described as follow.

6.2.1.1 Baggage Handling System

The Baggage Handling System (BHS) is one of the constituent systems of airport SoS. It can be considered as the heart of the airport system. It is a collection of high-tech components and subsystems working together as a Systems Engineering model to handle passengers' luggage in a fast, safe and precise way. As airports are operating larger aircrafts, handling large number of baggage has its own complexity and an intricate process. One of the main challenges for expansion of Changi at T3 was to link the new system to the old ones at T1 and T2 that can be assumed as its legacy systems. Although the arrival of supersize aircrafts such as the A380, demand a rethink of details such as the presentation lengths of baggage carousels.

Baggage handling system design and construction for T3 was done by a consortium comprising Denmark's FKI Logistex and Singapore's Inter-Roller Engineering Ltd. The complete system consisting two tilt tray sorters that have one kilometer length each and fed by twelve conveyer belts from departure zone, costing about S\$121 million (Figure 6-5). The concept of using tilt tray sorters was to allow passengers to check-in from any six departure points so

called universal check-in. With this system, six to eight flights can be processed per each departure point, thus leading to significant time-saving for ground handlers. This system also used in T2 and integrated to other two terminals.

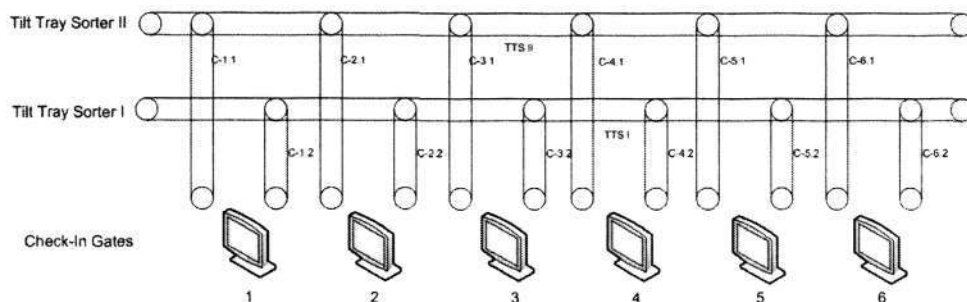


Figure 6-5 Tilt Tray Sorter Schematic

For the first time in the region, in terminal 3 CrisBag system have been introduced. Old infrared technology that usually used in airports switched to Radio Frequency Identification (RFID) system that has a higher reliability than the barcode reading. The Crisbag system consists of a variety of straight elements, curve elements, mergers, diverters, vertical lift units and discharge devices that is a very complex system by its own and is one of the airport SoS constituent systems. Study of bad experiences in Denver Airport baggage handling system design, shows how much a BHS complexity could affect an airport overall system's operations and reputation.

The other new high technology system that has been used in terminal 3 is Early Bag Storage (EBS). This system specially designed for transferring passengers that check-in early. All checked-in baggage stored in predefined spaces, waiting for future call. Very fast travelling belts, intelligent empty tote induction and baggage stuck in system permit the system to raise its peak capability.

This efficient BHS system that linked to all three terminals, allows bags to be transported and stored from aircraft to aircraft within 35 minutes (Lim

2008). A standard time of 60 minutes set by CAAS to move luggage between terminals and onto aircrafts. The BHS can handle 2700 bags per hour per line.

In baggage handling system architecture, several screening process levels have been conducted. Besides determining RFID tags that shows passenger particulars, flight number, destination, etc. security is the most important issue that screen in different five levels. X-ray machine generate bags image and automated evaluation proceed by the machine in the first evaluation level. The other four levels also used computer Tomography and experts officers.

6.2.1.2 Air Cargo

Air cargo system is one of the most important parts of each airport, that playing a distinct role in its commercial benefits. In 1992 the concept of global transpark (GTP) was proposed. Several describing models also presented to better understanding of its importance. FedEx key hub, Subic Bay in Philippines is an important model because the major air freight companies established their own mega hubs at the global interstices of their business in Changi Airport. (Sit 2004)

Singapore's extensive network of Free Trade Agreements, Avoidance of Double Taxation Agreements and Investment Guarantee Agreements, as well as its comprehensive air, sea and IT infrastructures, provides for the seamless flow of goods and services to markets around the world.

Sit (2004) presented four main Infrastructures of any possible GTP as follow:

- ❖ A multi-model transport hub with air cargo facilities at the core, linked directly to efficient expressways, rail and water transport, integrated as a new transshipment centre.
- ❖ An advanced telecommunication and e-commerce centre, linked to the hinterland and to the world, for instant data assembly,

processing and transmission with a view to extending and intensifying market coverage and material sourcing.

- ❖ Development of industrial sites for agile manufacturing for a global market.
- ❖ Development of a trade and warehouse centre for both the regional and the global market.

Study of Changi airport and its master plan proved the compatibility of its unique position and good management to be a global cargo hub. Consultants and Changi managers understood the structural changes in international business of airports, and implemented other's good practices for T1 to T3 very well. SoS characteristics like core leadership and evolutionary could be delivered easily. In Figure 6-6 and Figure 6-7 Changi air cargo depicted. Basic infrastructures like telecommunications and e-commerce are the well developed infrastructures in Singapore. Specially in Changi airport they used technology know-how very well.

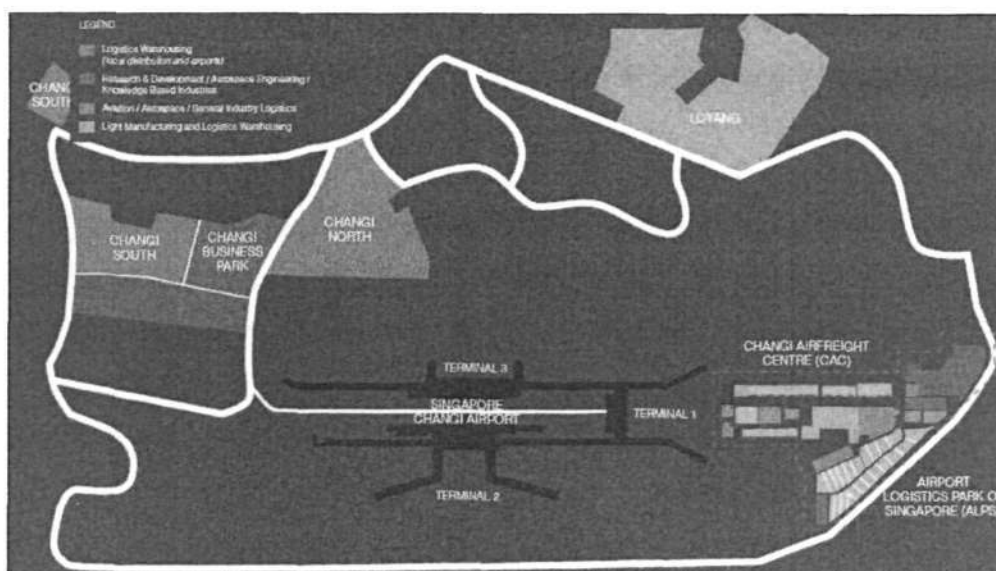


Figure 6-6 Map of Changi Airfreight Centre (CAC)(Changi 2008)

Access to other transportation modes like rail, road and sea, developing warehouses and aviation manufacturing also considered in evolutionary development of Changi phases. All together caused Changi Airport to be ranked top on the Ease of Doing Business in World Bank's annual Doing Business Report for 4 years from 2006-2008. SoS view in airport management and pay more attention in different aspects of this big enterprise made Changi Airport one of the best in the East and Southeast Asian mega regions and development corridors.

The other evolutionary development growth of Changi Airport is not only to be the number one in passenger and cargo hub, but also the best maintenance hub for aircraft manufacturing and airlines.

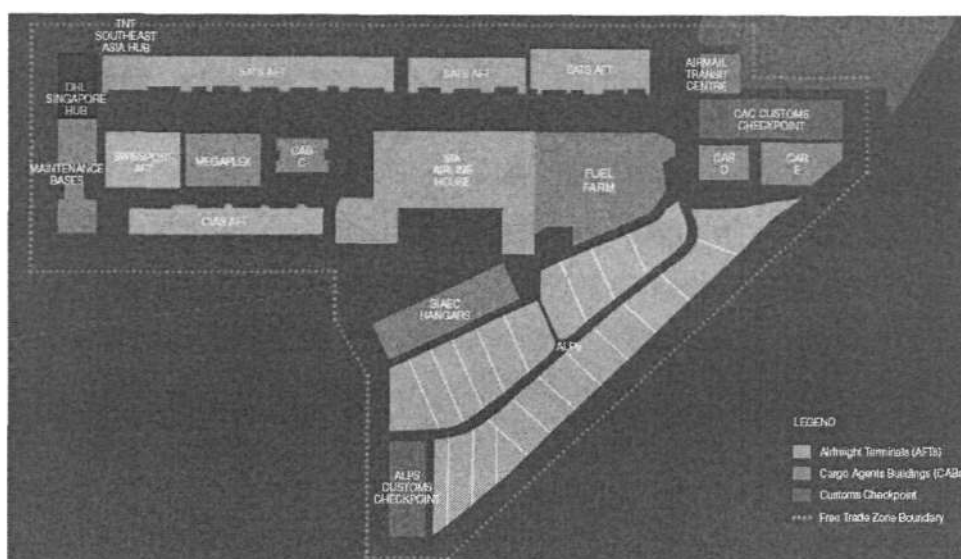


Figure 6-7 Airport Logistics Park of Singapore (ALPS)(Changi 2008)

As it shown in Figure 6-9, Manufacturing contributes about 25% to Singapore's GDP. By 2018, Singapore aims to raise manufacturing output from S\$238 billion in 2007, to S\$300 billion , by strengthening its capabilities in key industries such as electronics, chemicals, biomedical sciences, aerospace engineering and telecommunications, while venturing into new areas of growth, such as nanotechnology, environment and water technology(Changi 2008).

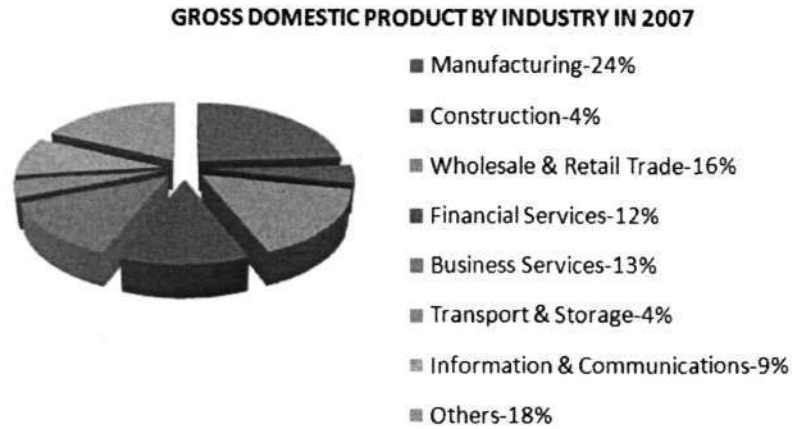


Figure 6-8 GDP by industry in 2007 (Changi 2008)

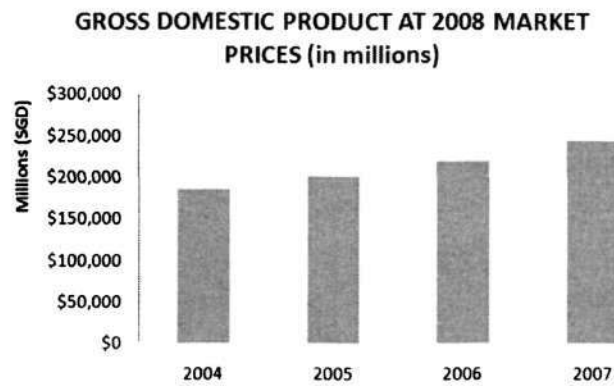


Figure 6-9 GDP at 2008 market prices (Changi 2008)

As the goods transportation, Cargo is one of the major parameters in air hub marketing, Changi Airport should expand its capabilities in this field also. The contestability hypothesis for Airports and Air-hubs has been raised in 1995(Donne 1995) . The major competitors in East and Southeast Asia region are depicted in Table 6-1 (Hufbauer and Findlay 1996).

Table 6-1 East and Southeast Asia region Cargo Competitors, 2008 (ACI 2009)

Airport	Country	Total Cargo *
Hong Kong International Airport	Hong Kong	3,660,901
Incheon International Airport	South Korea	2,423,717
Narita International Airport	Japan	2,100,448
Changi International Airport	Singapore	1,883,894
Taiwan Taoyuan International Airport	Taiwan	1,439,120

*Total Cargo: loaded and unloaded freight and mail in metric tonnes.

6.3 Privatization, a step forward to Managerial and Operational Autonomy

Airports are generally seen as attractive complex system to investors for several reasons. The fact that airport industry has strong growth potential could be an important reason. Many airports, particularly the major ones, face limited competition, both from other airports and other modes of transport. Large capital investment needed and difficulties in finding appropriate, convenient locations where airport development allowed are only two of the high barriers to entry within the industry. However risks clearly exist as well, such as political interference in the form of airport regulation and control over airport developments such as deregulations and greater collaboration through alliances. Carney (Carney and Mew 2003) mentioned that airport privatization can occurs in different ways. These types broadly fall into five categories: (Graham 2008)

- Share flotation
- Trade sale
- Concession
- Project finance privatization
- Management contract.

The selection of most appropriate type of privatization is a complex decision making process that directly related to government's objectives in seeking privatization.

The 1990s were the decade when airport privatization became a reality. Privatization is usually associated with the transfer of the management of an airport, and in many cases the ownership as well, to the private sector. It will reduce the need for public sector investment and provide access to commercial markets. It will reduce government control and interference and may increase an organization's ability to diversify. It may bring about improved efficiency, greater competition, wider share ownership and provide greater incentives for management and employees to perform well.

By privatizing Changi Airport, Temasak Holding Company won the bid and Changi Group (one of the Temsak Subsidiary companies) is responsible for managerial and operational activities of Changi airport. Serving more than 80 international airlines flying to more than 190 cities in 60 countries, Changi Airport handles more than 4,500 arrivals and departures weekly and over 37 million passengers a year. That is more than 7 times the size of Singapore's population. With over 40,000 square meters of commercial space, Changi Airport Group is also the landlord for Singapore's largest shopping location.

Corporatization of Changi Airport has been brought more flexibility in managerial issues. Now CAAS's main job is to be in charge of regulatory issues and more focused on investment in overseas and study of possible ways to change Changi to region's main Air-hub.

6.4 Analyzing the SoS attributes

Using available information, Changi Airport SoS attributes has been analyzed and scored. Statistics shows, more than 60% of the annual revenues of the airport comes from the non aviation related business (Jarach 2005). So analyzing the commercial constituent systems of Changi is as important as aviation related systems. Table 6-2 describes analysis of attributes. This table is a part of the frame work that described in Chapter 5.

Table 6-2 Changi Airport SoS attributes Analyze

Main char.	Analyzing attribute	Changi Airport	Score
Autonomous	Operational independence	Most of constituent systems in all integrated airport can operate independently. This attribute is stronger in commercial systems(Jarach 2005).	3
	Managerial independence	Privatization and transfer of managerial functions of airport to Changi group increase managerial independency as a whole. Also each of the constituent systems manage themselves independently, and similarly commercial constituent systems manage themselves completely individually.	2
	Own business process and Own budgets	Commercial constituent systems have their own process and budgets, although some of aviation related systems take feedback from other systems in their process(Lim 2008).	2
Core leadership	Information/ Knowledge management	Several Data bases manage information flow between different systems like: ATC, Security system, Apron Control, Staff information, schedule and reports. Documentation and logs are crucial that should be saved securely in data centers for future strategic planning.	3
	Net centric issues/planning and process development	Each of the main three terminals and budget terminal working as a network to service passengers and airlines. Several networks link these four terminals together in different area of transportation, data, BHS...	3

Chapter 6: SoS FRAMEWORK VALIDATION

	Coordination of functions	An integrated computer system and information technology as intranet and using high speed internet provide value-added services to their customers in passenger or goods transportation. Changi Group as a lead system integrator coordinates functions of constituent systems via producing procedure to target the main goal(Changi 2008; Lim 2008). Ranked Top on the Ease of Doing Business World Bank's Annual Doing Business Report for 4 years from 2006-2008	3
Convergence in purpose	Avoid of concurrent Activities	Changi management provide a competitive environment for systems to compete each other for better services (airlines, commercial tenants ...) and to eliminate duplication of activities(Lim 2008). Most Competitive Place for Business KPMG's Competitive Alternatives Study 2006	3
	Connectivity	All systems connected to each other properly as an integrated system. Security cameras, gate electronic opening codes, BHS, flight information system,	3
	Have a joint mission	CAAS as a regulatory issue and Changi Group in charge of managerial issues lead the SoS to have the best effective, efficient Air hub. Ranked Top for Quality of Air Transport Infrastructure World Economic Forum's Global Competitiveness Index 2007-2008	3
Evolutionary	Evolutionary development	Development of Terminal 1 to 3 and Budget terminal took place during years 1975 to 2008. Demand forecast and long strategic plans made Changi development evolutionary. Even though possible planning to establish new terminals is in the order. (Appendix B)	3
	Dynamic capability	As part of Changi master plan, the current facilities of T1 and T2 were reviewed to look into possible ways of	3

		increasing their capacity, whether through adopting technological innovations or adopting efficient passenger processing systems. Dynamic monitoring of demand and competitor expansions lead CHANGI decision makers to do strategic planning for future.	
Diversity	Heterogeneous constituent systems	Different systems of commercial, aviation related, tourism, food and beverages ... working together. Some advance systems using very high technology like BHS, Security and detection, Sky train, linked to other traditional systems(Lim 2008).	2
	Mix of existing and New systems	Every time a new terminal established there was a concern of coupling new and old systems. Combining T3 to existed T1 and T2 in mostly all of the systems specially BHS already well done.	3
Interoperation	Interoperability of constituent systems	All constituent systems receive and transmit feed-backs from and to each other to synergize the main goal. In 2000 Changi airport was awarded by IATA “ Best Airport Worldwide” in the category of more than 25 million passengers per year(Jarach 2005).	2

The results achieved form above table depicted in a radar graph for better representation. A full circle means all attributes and characteristics satisfied by the organization.

Changi Airport Attributes, SoSness

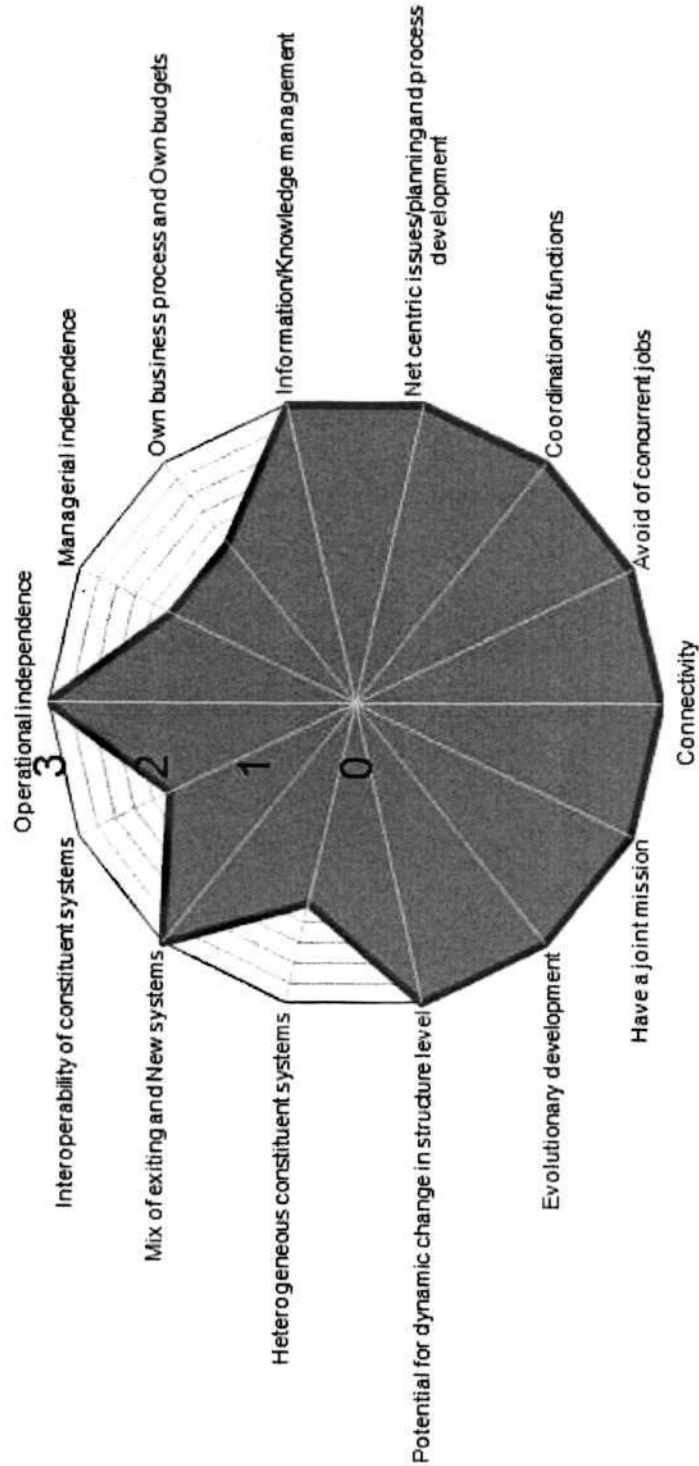


Figure 6-10 Changi Airport SoS Attributes, SoSness

Just to better demonstration Figure 6-11 depicted SoS characteristics of Changi Airport. Autonomous supposed to be improved after privatization of Changi airport. Diversity of constituent systems is also increasing with involving lots of commercial enterprises.

Changi Airport SoS Characteristics

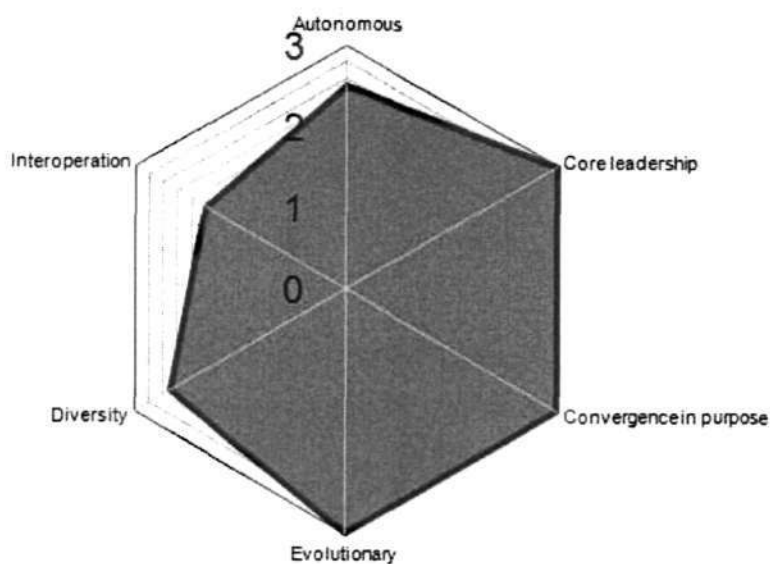


Figure 6-11 Changi Airport Characteristics

Study of Changi SoS characteristics and according to the Maier's SoS categorization explained in section 0 It could be concluded that Changi Airport is a closed collaborative SoS.

6.5 CHANGI Airport Hierarchical lexicon model

Different levels of SoS lexicon model for Changi Airport was previously depicted in Figure 6-4. In the following, Table 6-3, description of all four categories of Resources, Operations, Policy and Economy associated with different levels explained. The interconnection between layers is in a top-down hierarchical order. In higher levels like δ or ϵ SoS characteristics are stronger. Moving from top to down, SoSness decreases and most of the constituent systems in α or β level are good examples of systems engineering models. Some of them like Air Traffic Control and Baggage Handling System are very complex by themselves. SoSness and SoS levels do not follow a certain equation of linearity or hyperbolic. Figure 6-12 depicted this behavior.

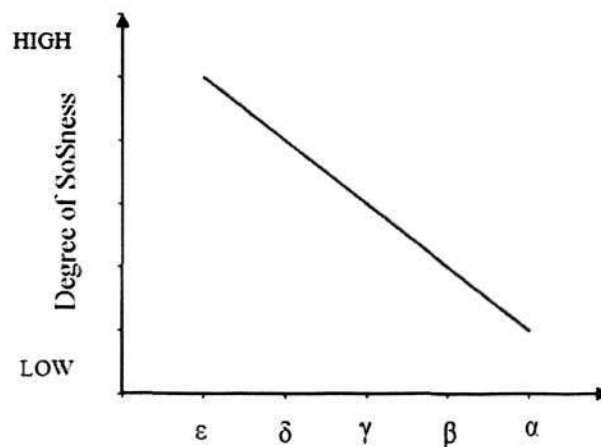


Figure 6-12 SoSness and SoS levels

Usually in SoS problems external forces like Economy and Policy play an important role. By privatization of Changi Airport, CAAS can focus on possibility and powerful criteria of changing Changi to an Air hub. Also CAAS should grow on the potential of huge investments on Aircraft industries in excellent condition of Singapore infrastructure and open mind government. With more focus on maintenance hub Singapore has the potential to be the first choice for Aircraft industries. On that time analysis of Changi SoSness will have new aspects. Using further demand prediction, yet to be design aircraft should be consider as a necessary link to Airport management.

Table 6-3 Changi Airport lexicon model levels

Level	Resources	Operations	Policy	Economics
ϵ	Global transportation system	Global operation in world transportation system	Global policies relating to world transportation system (e.g. Standards, rules, etc.)	Global economies of the world transportation system
δ	Multiple interwoven regional/sector (e.g. Resources of Singapore NTS)	Operations of multi business sectors (e.g. Operations related to Singapore NTS)	Policies relating to multi business sector (e.g. Policies issued by MOT)	Economic of collection of sectors (e.g. NTS Economy, Singapore Air hub)
γ	Resources in regional sector (e.g. regional resource, manage by Changi Group)	Operating collection of resource network(e.g. Operation of CAAS regulations)	Policies relating to each regional network(e.g. Policies and regulation by CAAS)	Economics of each business sector (e.g. economic of airport, commercialization)
β	Collection of resources with a common function (e.g. Each of the terminals, data servers, cargo etc.)	Operating resource networks for common function (e.g. Operation of airside and landside, airlines etc.)	Policies relating to multiple resources (e.g. Policies related to environmental air traffic)	Economics of operating/buying/ selling/leasing resource network
α	Physical assets, facilities and infrastructures (e.g. BHS, Security and Detection, Runways, CCTV etc.)	Operating a resource (e.g. Operation of systems, control tower, ATC, etc.)	Policies related to each resource (e.g. How to maintain systems, people in charge etc.)	Economics of buying, selling, leasing and operating of each resource

Other Airports General Comparison

Study of SoS characteristics especially in infrastructure domain, needs to be compared with other successful projects to give a better insight to the Changi success. To have a general comparison, Heathrow Airport, Kuala Lumpur international Airport (KLIA) and Hong Kong International Airport are considered. Planning to change Changi Airport to region Air hub in passenger and good transportation, needs a careful study of its competitor's short and long term strategies.

6.5.1.1 Heathrow Airport, T5- London, UK

Heathrow Airport is one of the busiest airports in the world. Approximately every 45 seconds one flight lands or takes off. After operating terminal 5 it handles more than 63 million passengers per year. About £2.5 billion spent to build Heathrow terminal five. More than 20,000 organizations have been involved in Heathrow terminal five during its years of designing, planning and operational readiness. British Airport Authority limited and key stakeholders such as British Airways, and the control authorities are the most important organizations. They built Heathrow T5 based on what they learnt from successes and failures from around the world (Doherty 2008). It is a logical way for such critical infrastructure projects with huge amount of investment that had similar projects operating somewhere in the world to learn from their good lessons and experiences.

With all of these shiny points and new investments in terminal five it is still far from achieving its goals as a high performance airport. It was in the news that: "London's Heathrow Airport has been voted the worst airport in the world for the second year running in a poll of 14,500 frequent fliers while Singapore's Changi was again ranked as the best." *SYDNEY, Oct 23, 2009. (REUTERS 2009)*

These surveys are done by some survey companies. In aviation, SKYTRAX is one of the most famous one, the mentioned ranking is based on their survey. It mostly related to quality of services to passengers and satisfaction of staff in their working environment(SKYTRAX 2009).

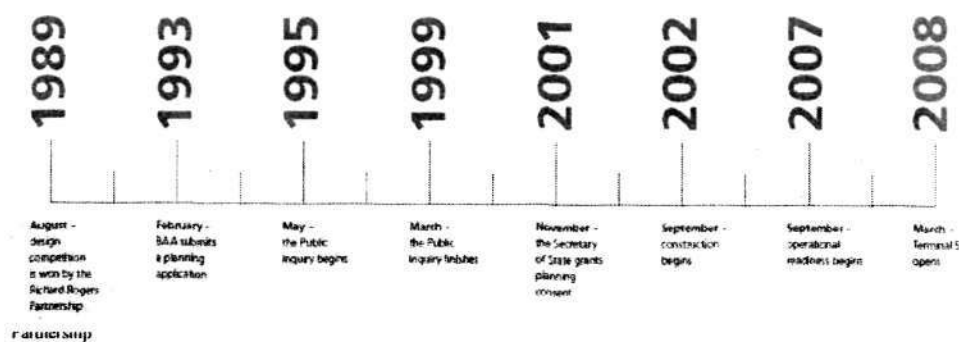


Figure 6-13 Heathrow T5 long decision-to-operate period (Heathrow 2009)

Heathrow had a very bad reputation in baggage handling system before opening terminal 5. Statistics shows more than one million baggage losses per year. In new terminal using a very high-tech baggage handling system, they try to overcome this big problem.

30 miles out of Heathrow, inbounds are routed into four corkscrew holding patterns called stacks, planes enter stack around 15,000 feet and exit at 7,000 feet. Similar scenario for outbound planes has been designed. Using these stacks cause Heathrow to be successful in maximum tuning of planes, using only its two runways. Table 6-4 depicted European Hub Airports land take in 2004. Heathrow has the best efficiency in land use between its competitors.

Table 6-4 European Hub Airports Land Take 2004 (Doherty 2008)

	Land Take (ha)	Pax	2006 Runways	2010 000pax/ha
Heathrow	1.227	67.1 mppa ²	2	54.7
Paris(CDG)	3.309	51.0 mppa	4	15.4
Frankfurt	1.397	50.8 mppa	4	36.4
Amsterdam	2.147	42.4 mppa	5	19.7

Heathrow Airport in UK and JFK Airport in US could be good examples of success and failure experiences for South East Asian Airports. Accessibility to different resources and high technology software and hardware to manage resource allocation, increase the expectation level of investors to have a quick projects. Although it is a proved rules in project management that each project has a acceptable time and delay. As it depicted in Figure 6-13 decision to operation for Heathrow Airport takes 21 years, which is really long time.

In East Asia Changi airport has two main competitors. Hong Kong International Airport and Kuala Lumpur international Airport are the two active competitors. In Table 6-5 the SoS characteristics for these two airport considered.

² mppa : Million passenger per annual

Table 6-5 Changi Competitors SoS characteristics

Characteristics	Hong Kong Int. (HKG)	Kuala Lumpur Int. (KLIA)
Autonomous	The Airport operator is Airport Authority Hong Kong, a statutory body wholly owned by the Government of Hong Kong. *Had several bad experiences in start up.	The airport is operated by <i>Malaysia Airports</i> (MAHB) public limited co., 100% owned by government of Malaysia. KLIA is also the main competitor for Changi in stopover point on the <i>kangaroo route</i> ³ . *Had several bad experiences in start up.
Core leadership	The Airport Authority formulated a "push and pull through" strategy to expand its connections to new sources of passengers and cargo. They connected airport to other three kind of transportation mode coach station, ferry station and rail network to have the best service for their passengers that is their main goal. (Intermodal Transportation)	KLIA well connected to rail network and Both public and private buses connect KLIA to several points in Kuala Lumpur and beyond. Even though with usual constraint in governmental management KLIA connected to public transportation in a proper way.
Convergence in purpose	Since the opening of HKIA, the <i>Hong Kong Special Administrative Region Government</i> has implemented a policy of progressive <i>liberalisation</i> of air services with the intention of promoting consumer choice and competition. Many <i>low-cost airlines</i> have started various regional routes to compete head-on with full-service carriers on trunk routes.	The purpose of building Low Cost Carrier Terminal (LCCT) specifically at KL International Airport was to cater the growing passengers of the low cost airlines, especially the passengers of Malaysia's "no-frills" airline, <i>AirAsia</i> . The number of this passenger type is growing day by day in this region and AirAsia is one of the pioneers in this category.

³ Traffic between Europe and Australia

Evolutionary	<p>Airport Core Program, terminal 1 in 1998 and terminal 2 in 2007 officially opened. A study for the HKG Master Plan 2030 is underway to examine whether and how infrastructures at HKG - including airport access, terminal and apron facilities and a new runway - should be developed to support the economic growth of Hong Kong and the region.(HKIA 2009)</p>	<p>The master plan of Kuala Lumpur International Airport involves constructing five runways, and two terminals accompanied by two satellite terminals for each terminal over three phases. Ultimately, the airport will be able to handle 100 million passengers per annum once all three phases are implemented.1998-2020 (Appendix A)</p>
Diversity	<p>At present there are 49 frontal stands, 28 remote stands and 25 cargo stands. Five parking bays at the Northwest Concourse are already capable of accommodating the arrivals of the next generation of aircraft. A satellite concourse with 10 frontal stands for narrow body aircraft is under construction to the north of the main concourse for commissioning by the end of 2009, bringing the total number of frontal stands at the airport to 59.</p>	<p>consists of more than 40 aviation related systems and airport functions including air traffic management, baggage handling, passenger check-in and flight information display, also lots of commercial systems (ACI 2009)</p>
Interoperability	<p>For three to five months after its opening, it suffered various severe organizational, mechanical, and technical problems, FIDS problem, cargo data server (Lander 1998; Gordon 2004)</p>	<p>The inauguration of the airport was marked with problems. Aerobridge and bay allocation systems broke down, queues formed throughout the airport, and baggage handling broke down, with lost bags and waits of over five hours. Most of these issues were sorted out eventually, but the baggage handling system continued to be plagued with problems, and it was finally put up for a new complete replacement tender in 2007. (Berhad 2008)</p>

For better understanding of mentioned comparative table (Table 6-5) and demonstration of SoS characteristics of Changi, KLIA and HKIA airports, they depicted in a single radar chart.(Figure 6-14). Base of scoring have been mentioned in Table 5-2, and some of related evidences shown in Table 6-5.

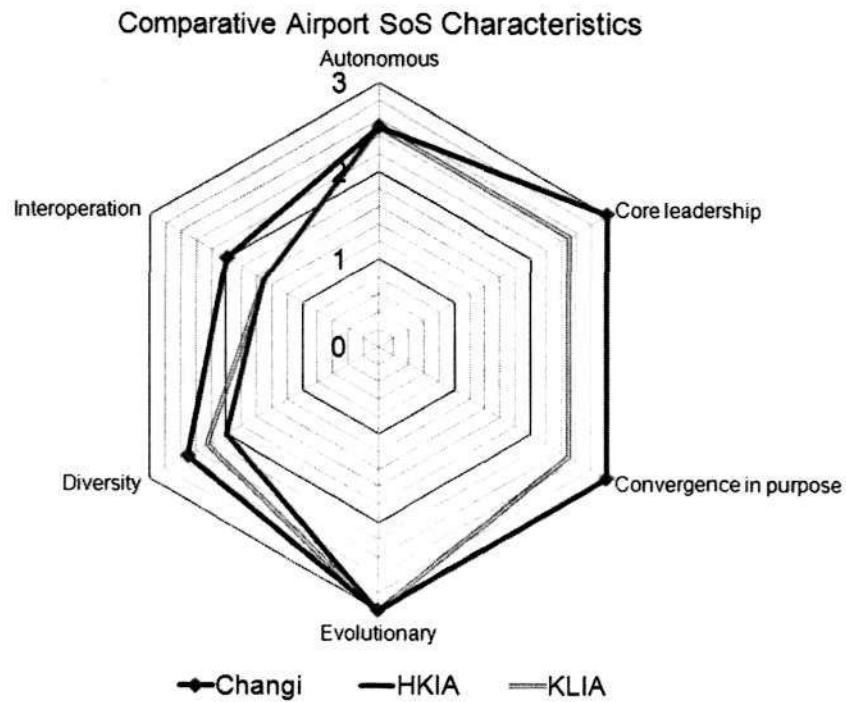


Figure 6-14 Comparative Radar Chart

Chapter 7 CHANGI AIRPORT LESSONS LEARNED

In this chapter using Pettigrew (1987) three classes of variables (Figure 7-1), author try to present successful lessons of Changi Airport in management of strategic change that brought Changi a top ranked world class airport. The main goal is to highlight the role of SoS characteristics in management of different variables.



Figure 7-1 Strategic Change Variables (Pettigrew 1987)

Figure 7-1 depicted, the management of strategic change involves consideration of all three variables of a chosen strategy, Content, process and the contexts in which it occurs. The context variable consists of inner and outer contexts. Inner context refers to the structure, corporate culture and political context within the organization. Outer context refers to the economic, business, political and societal formations in which organization must operate. The process of change refers to the actions from the various interested parties are looking how to change an organization status from its present to its future state. So in strategic change questions could be categorized as: ‘what’ of change in content, ‘why’ of change in inner and outer context, and ‘how’ of change can be understand from an analysis of process.

These three variables developed further by Yeo as a framework in information system projects (Yeo 2002).

In this chapter major lessons of Changi Airport, as a world class Airport are collected and presented. Table 7-1 depicted the strategic change management variables and SoS framework that are the foundations of these achievements.

Table 7-1 Strategic Change variables and SoS framework

Strategic Change Variables		Content	Process	Inner Context	Outer Context
SoS Framework	6 Characteristics	Diversity Interoperation	Autonomous	Evolutionary Convergence in purpose	SoS δ and ϵ level
	14 Attributes	Mix of existing and new systems, legacy use	Operational Independence	Dynamic Capability	Government (agencies, authorities) role
		Interoperability of constituent systems	Managerial Independence	Evolutionary development	Global and local economy
		Heterogeneous constituent systems	Own business process and own budget	Interrelationship and connectivity	Governmental policies
				Have a joint mission	Social behavior
				Avoid of concurrent job	
Strategizing Organization and Business process				Singapore Geographical Location	
Corporatization, Privatization				Open Governmental rules and regulatory	
Commercialization				Dynamic Economy	
Training the people					
Environment friendly, Climate change issues					
Increase Performance using Technology					

7.1 Outer Context

No one could explain Changi airport success without emphasizing on Singapore government role. As mentioned in 0 Mr. Lee the Prime Minister of Singapore (1959-1990) played a significant role in Singapore development and in specific Changi Airport. Good time and budget management plus good estimation of future air traffic are the other important factors in Changi success. Also, government policy to use English language as the official language of the country, and improved communication in different levels should be considered. Singaporeans can speak fluent English which is a huge plus in today's IT world and essential need for such a developed country.

Infrastructural success is obtained from successful operation and management of network of systems in different domains of social, economical and political.

Changi's staged development could be considered as a part of Singapore globalization policy that is : "the integration of Singapore economies into the international economy through trade, foreign direct investment, capital flows, migration, and the spread of technology". Singapore government with its long-term strategic planning try to make Singapore as a regional hub.

Singapore strategic geographical location also should be considered as an important factor that increased development and absorbance of foreign investment.

Some of the other influences affected success of Changi airport are listed as follow (Mirror 2009):

Singapore:

- It is one of the cleanest cities in the world, consequently its Airport.
- It is a green city - greenery all over the city. Appropriately, it is also called a 'garden city'
- Its port is the busiest port in the world - handling about 29 million TEU's (Twenty Footer Equivalents) per annum, case of Intermodal Transportation.
- It became a first-world country from a third-world country in one single generation. It was one of the poor countries in 1965 when it was separated from Malaysia. In 35 years, it is one of the wealthiest countries of the world.
- Its public transport system should also be one of the best in the world which comprises of buses, trains & taxis. Buses and trains are almost always 100% on time and are very frequent in service. Case of Intermodal Transportation.
- Its Government departments should also be the most efficient. Response time is minimum, work moves very fast here
- Its infrastructure is also number one in the world. This includes world's best airport, world's busiest port, a very efficient and highly successful telecommunication network, highly efficient water & electricity system, no-traffic-jam roads, world's best airline, reliable, air-conditioned & most efficient public transport system, most efficient Government departments, public amenities, housing, industrial land, office buildings, world class banks, most modern post offices, world class insurance companies, multi-channel TV stations etc. etc.
- It has also been voted as the freest economy in the world - a hassle free, no-red-tape country

7.2 Process

In planning T3 with good experiences of T1 and T2, finding an optimal plan for the new terminal was a key aspect of planning. The other evaluation criteria beside shape of T3 that could be mentioned as: number of connected gates, obstructed gates, contact gates, clarification of passenger flow, aircraft circulation, aircraft taxi distance, construction phasing, interconnectivity and terminal integration with T1 and T2, landside access, walking distance, baggage/cargo operations, baggage travel time, MRT station link, amount of land used, number of decision points (passengers), and number of decision points (roads) (Lim 2008).

In section 6.3 Changi corporatisation process was described. Since it is newly changed, it needs time to assess the effects of Changi corporatisation. The main achievement is operational and managerial autonomous. Some of the constituent systems working in Changi Airport that are result of good management decisions and use of technology to increase the performance described as follow:

Automated People Mover System (Skytrain)

“The seamless transition from the old system to our new Skytrain system is our pride and joy. Our Skytrains have become the arteries of this airport, carrying smiling airport users.” (Kashiwa Makoto, PM, Mitsubishi Consortium)

Skytrain system costing S\$142 million now facilitates the smooth transfer of passengers among all three terminals at both airside and landside. To avoid clashing with underground facilities like MRT line and Baggage handling system, present design of Skytrain was approved and constructed. There were other considerations for the design of the Skytrain, one of which was capacity. Airlines required sufficient capacity for carrying transfer load efficiently. There

are a total of seven stations and 6.4 km of guideways. Each train can take a maximum load of 97 passengers(Lim 2008).

Low Cost Carrier (LCC)

Establishment of Budget Terminal as a low cost carrier beside other terminals was one of the important decisions taken by CAAS, to compete with other region airports regarding cheap flight passenger demands. The Low cost model attributes could be depicted as Figure 7-2.

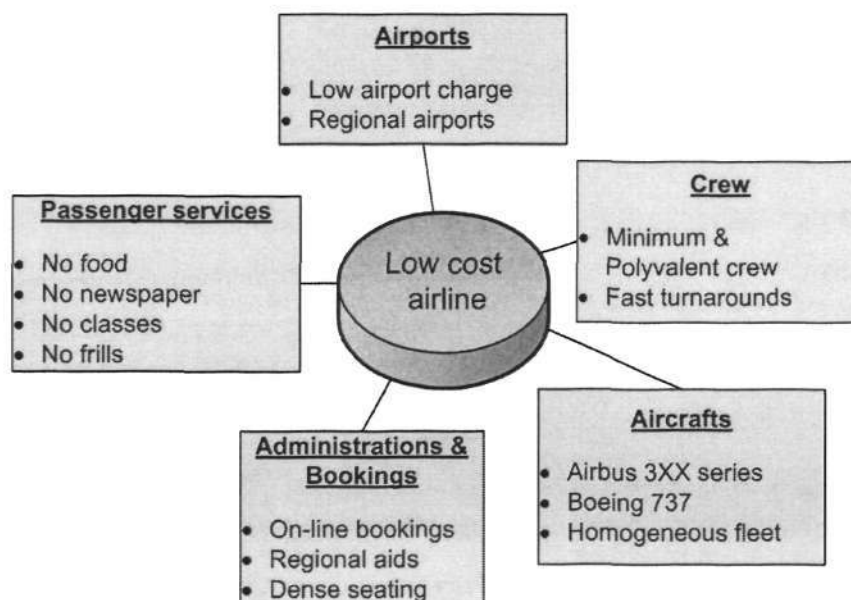


Figure 7-2 Low Cost Carrier attributes

A former monopolistic environment in aviation transportation has turned into a competitive one with tight operational margins. This competition brings new sources of tourism, employment, and economic development for its region. In the US, Low cost models initially conceived to compete with coach services, are currently shortening distance catchment areas, from the initial 1000 km to 600-700 km (Michael Pickhardt 2006).

Homogeneous fleet helps the system to reduce pilot and maintenance costs, since use of minimum number of aircraft models is easier to manage. Online ticket and services sales instead of traditional distribution channels such as travel agencies cut the extra charge of middle-men and sales staff expenses.

Tiger Airways, Jetstar Asia Airways, and Valuair are the three Singaporean Low-Cost Carrier Airlines that are working in Southeast Asia. They use Budget terminal as their main hub to several destinations defined for such LCC airlines. Figure 7-3 depicted Tiger Airways routes in Singapore region. These airlines have several powerful competitors like AirAsia (Malaysia), LionAir (Indonesia), and One-Two-Go (Thailand). It is the competition of ticket price, quality of services on air and in airport. Changi management has decided to renovate Budget terminal as well as T1.

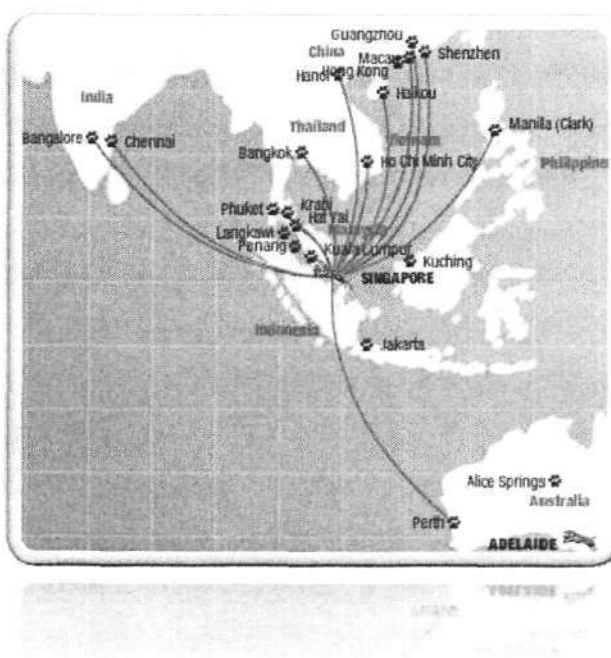


Figure 7-3 Tiger Airways Singapore routes

The “Fast turnarounds” is the other important point in LCC airlines. For a LCC the reference time to turnarounds in landing and takeoff is 25 minutes. The longer each aircraft is flying, the more profit obtained. It mostly rely on airports LCC airlines use. Singapore Budget Terminal is a good model of non

congested airport with good facilities where LCC have optimum conditions to rapidly operate.

Changi Budget Terminal and consequently Singapore LCC Airlines should try to achieve its own network of destinations.

7.3 Inner Context

Establishment of Changi airport had evolutionary stages from planning to operational readiness for each of terminals 1 to 3. With technology development and growth of air travelling demands Changi terminals developed one by one. Each of the new terminals should connect and use its legacy resources of previous terminals. In most of the cases like BHS, check-in system, flight information system an incremental change was dominant and with the new proven technologies they switch the old system to a new integrated one. In future, increase of air traveling demand may recover the huge cost of land reclamation to build Changi terminal 4.

Check-in system, flight information systems, baggage-handling systems, automated people mover system, immigration clearance systems, passenger careening procedures and security equipment, are all critical airport systems that have interoperation relationship to each other and designed to provide best services to passengers.

To prevent bad experiences of baggage handling system in opening KLIA and HKIA, operational readiness of T3 had 52 trails before actual operations commenced. The trail, at its most extreme, stress-tested the system where 800 personnel were tasked to check-in 10,000 bags over an 8-hour period(Lim 2008).

7.4 Content

This is about passenger's perception of the airport internal contents especially from design perspective. Most of the airport rankings are given high weights on passenger's feedbacks regarding their convenience, quick and simple procedures, attractive environment, accessibilities, variety of foods and beverages, temporary accommodation, etc.

From a design point of view, Changi Airport T3 efficiency was equated with simplicity and clarity. With the main focus on convenience of passengers, T3 planners designed passenger's process to be fast, smooth and stress free. T3 experience could be structured in two area of physical attributes of terminal in "Firmness" and emotional content in "Delight"(Lim 2008).

Firmness → Transparent Pavilion

In architecture innovation of T3 in terms of the use of transparency made it as a massive pavilion that everyone can enjoy watching the aprons, runway and sky of airspace in one clean sweep. Indeed, the high level of transparency also facilitates generous views between landside and airside as never before. It is one of unique design criteria of T3. Transparency facilitates the penetration of light, and natural daylight enters T3 from all directions.

Firmness → Skin, Cable- Net Wall

Following the design concept of open pavilion filled with natural daylight, designers proposed the Cable- Net Wall to maximize visual connection between the inside of T3 and its surroundings. The main characteristic of Cable- Net Wall was to be as weightless and as transparent as possible. The cable-net wall consists of several cables heavily tensioned to roof, floor beams and columns to form a fine net. This array of cables covered with laminated, tempered and heat strengthened glass to provide an optimal transparency.

To protect T3 pavilion from the intense heat of the afternoon sun, mechanically operated sun-protection louvers, designed and installed over the west face of the pavilion. These louvers move with the sun's angle to provide maximum protection.(Lim 2008)

Firmness → Twinkling Roof

The most dramatic feature of T3 is its roof. It is really a spectacular and unique roof experience that set Changi apart from other international airports. An array of 919 skylights, illuminating the interior of terminal completely with natural daylight for up to 8 hours a day, regardless of cloud cover (Lim 2008). Butterfly louvers on roof, control the sun light before passing through skylights.

These adjustable louvers are controlled by a computerized system that measures incoming daylight. To prevent damage of butterfly louvers because of probable strong winds, wind speed sensors provided on the roof to manage their position. On cloudy days, these louvers flip open to admit the maximum amount of illumination. Under the ceiling, there are arrays of perforated metal plates serving as an additional light modulating layer. They are totally 4321 panels (flip flops) in the terminal hall and 420 above the kerbside drop-off.

In project management point of view, because of simplicity and modularity of this roof design, it has a positive impact on construction schedule, budget, maintenance and life-cycle cost (Lim 2008).

Firmness → Sustainable and Intelligent Building Features

In Changi terminals and especially T3, idea of having sustainable, intelligent buildings with low environmental impacts was dominant. Rainwater coming from a catchment pond, collected in a huge tank at T2 and is used to water the plants and for flushing toilets. Singapore New water (NeWater) also be used for replenishing air conditioning systems and for fire protection purpose.

The use of natural lighting as a sustainable feature proved was a successful project. In energy management, the successful use of natural light reduce reliance on artificial lighting and cause a substantial reduction in energy consumption and therefore large saving in energy bills.

Extensive use of glass to create a transparent architecture has an unfortunate downside that heat can easily come inside, that demands higher mechanical cooling requirements. Various means have been employed to meditate stresses on air conditioning caused by the heat load transmitted through glasses. Low-E glass or double glazing, sun light sensors controlled butterfly louvers, and sunshades are some of good incoming-heat prevention examples.

Also escalators, toilet lights and some of air conditioning systems equipped with motion sensors to activate equipment and lighting only when the facilities are being used.

Delight → Spectacular Green wall

The idea of Green wall and multi storey vertical gardens comes from the CAAS policy to demonstrate Singapore's tropical climate in T3 design. Green wall is a 360 meters cable-net draped with creepers that stretched to divide landside from airside. Design and accomplishment of Green wall was not an easy project. A multi disciplinary project using technical innovation and horticultural know-how aimed to come up with the optimal condition to keep the creepers healthy. Type of stainless cables, irrigation method, humidity control system and other issues defined by engineers, that should be optimized by mechanical system engineers.

Use of flower's color is one of the clever organizational tools that have been used in Changi terminals to differentiate one terminal building from another. For example, In T2 plants with yellow flowers are making its theme. In T3 plants with red flowers are chosen to make different eye catching textures.

At T3, landscaping is no longer a complement to architecture; it has become a monumental feature that completes the architecture. The plants can flourish indoor because of unique roof design.

Delight → Art wall

In arrival hall, where passengers waiting to collect their bags at the baggage carousels get to contemplate a spectacular art wall. The art wall like the green wall, stretches the entire length of the T3 hall. The images of nature, from animals to flowers to trees, are carved on an off-white sandstone in an area of 360m long by 3m tall. Millions of passengers will pass through T3 each year and this huge art piece will inevitably catch their eyes.

The art wall is decorative and beautiful, but at the same time it is positive and enlightening and imparts an eco-message; a built-in subliminal message, lightly imparted, for all to be kind to our natural world(Lim 2008).

Using several SoS characteristics in planning and implementing of functions in different domains of Content, process and the contexts, caused Changi airport to be the number one airport in quality and services. Influence of these changes in different layers like: structure, corporate culture, political, economic, business, societal formations and organization operation could be a valuable lesson learned for future airport establishment or extension.

Chapter 8 CONCLUSION

8.1 Summary

East Asia region has an enormous potential of air transportation demand, because of the region's high population density, improving political stability, strong economic growth and widespread adoption of open skies policies. Many Asian region and countries like Hong Kong, Malaysia, Korea, China, and Dubai have undertaken expansions of their existing airports or plan to make new one, to be adapted to future demand as well as compete as regional air hub.

Singapore benefitting from its geographical location, well developed and severe infrastructure, accessibility of Air, Land and Sea transportation together in an accurate safe environment and good using of previous experiences and lessens have a great potential to be the number one air hub in this region.

By adapting SoS framework and implementing its characteristics in different stages of feasibility study to operational readiness of infrastructural projects like airports, achievement of superior success would be possible. However, Economic and political concern, as two effective aspects of critical infrastructure projects, with huge amount of investments and competitive environment make such projects very complex.

The report has presented a successful SoS framework could be useful for infrastructure decision makers and system architects as a reference model. Appreciating of SoS characteristics, in critical infrastructures domain contribute to superior investment and operational performance of Singapore's success.

8.2 Future works

For further studies, other Singapore critical infrastructures could be considered. Singapore with its rank number one in infrastructure could be considered as a successful model for developing countries. Other infrastructures like Land transportation system (including Bus and Train networks and Taxi management), Ports system, water and waste water network...could be studied to validate SoS framework. Even though each of the infrastructures could be compared to analyze the weak points and strong points of each system in terms of SoS characteristics. Although most of the critical infrastructures of Singapore were not designed and built through clear awareness of SoS characteristics, but its implementation process and outcomes are compatible to SoS framework. Study of effectiveness, efficiency and economics of these infrastructures shows that they are already using some of SoS framework characteristics in their organizations.

Connection of Airport to land and sea transportation system form an integrated national transport system and related challenges can be studied.

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ABBREVIATIONS

Abbreviations	Description
ALPS	Airport Logistics Park of Singapore
ATC	Air Traffic Control system
ATN	Aeronautical Telecommunications Networks
BHS	Baggage Handling System
CAAS	The Civil Aviation Authority of Singapore
CAC	Changi Airfreight Centre
EATCHIP	The European Air Traffic control Harmonization and Integration Program
EATMS	European Air Traffic Management System
EDI	Electronic Data Interchange
Eurocontrol	the European Organization for Safety and Air Navigation
FIS	Flight Information Services
GTP	Global Transpark
HKG/HKIA	Hong Kong International Airport
ICAO	International Civil Aviation Organisation
ITS	Intelligent Transportation System
KLIA	Kuala Lumpur International Airport
LTA	The Land Transport Authority
MOT	Ministry of Transport
MPA	The Maritime and Port Authority of Singapore
MRT	Mass Rapid Transit
NTS	National Transportation System
NYC	New York City
OLDI	On Line Data Interchange Protocol
PWD	Public Works Department
PTC	The Public Transport Council
SoS	System of systems
PSA	Port of Singapore Authority
TDB	Trade Development Board
TEUs	Twenty-foot equivalent units
TLC	New York City Taxi and Limousine Commission

APPENDICES

Appendix A: KLIA Operational Statistics

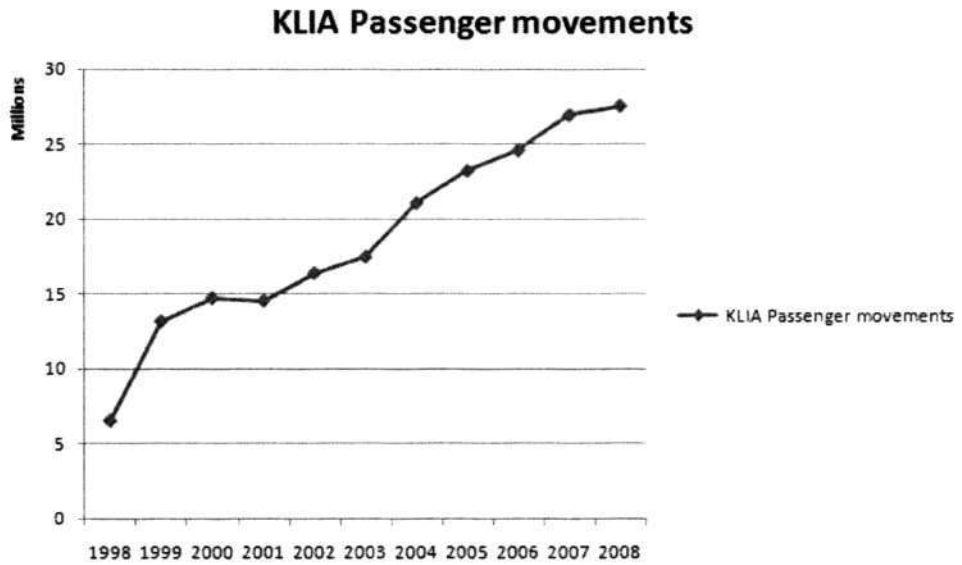


Figure AP- 1 KLIA Passenger Movements (Berhad, 2008)

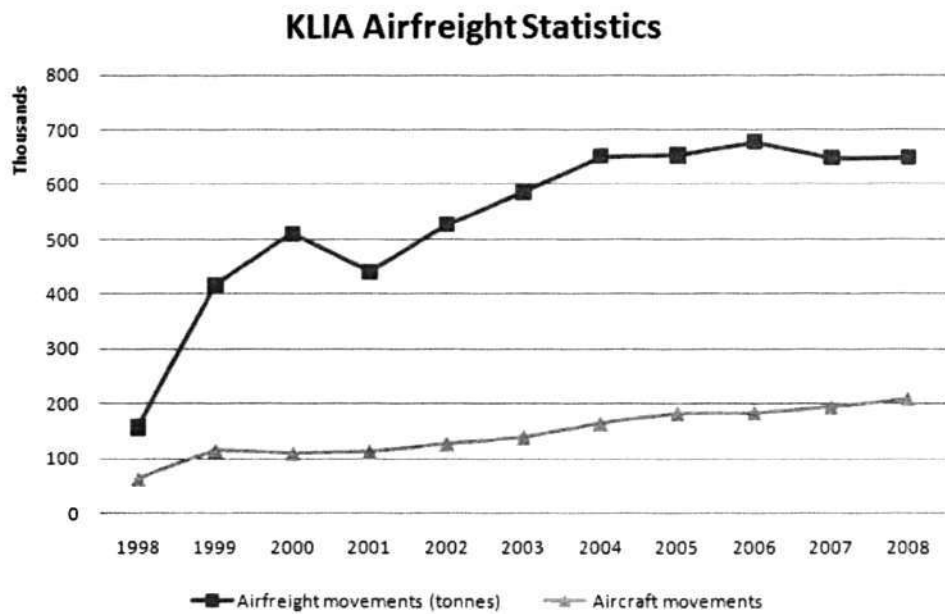


Figure AP- 2 KLIA Airfreight Statistics (Berhad, 2008)

Appendix B: Changi Airport Operational Statistics

Changi Airport Passenger movements

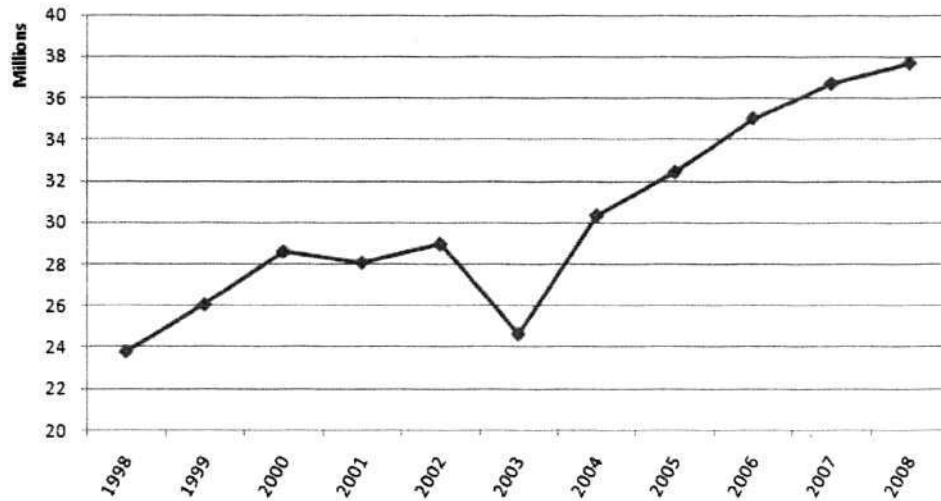


Figure AP- 3 Changi Airport Passenger movements (Changi 2009)

Changi airport Airfreight Statistics

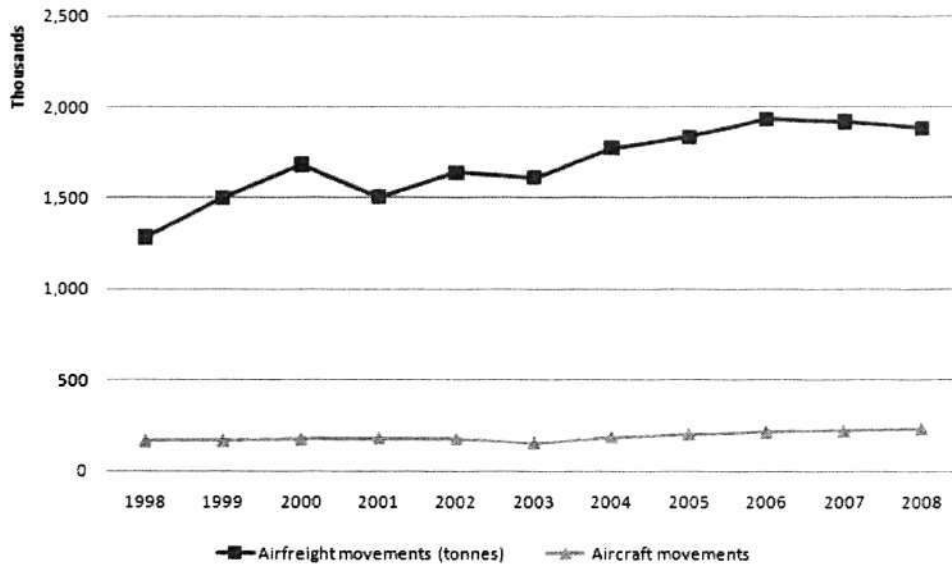


Figure AP- 4 Changi airport Airfreight Statistics (ACI 2009)

Appendix C: Hong Kong International Airport Operational Statistics

HKG Airport Passenger Movements

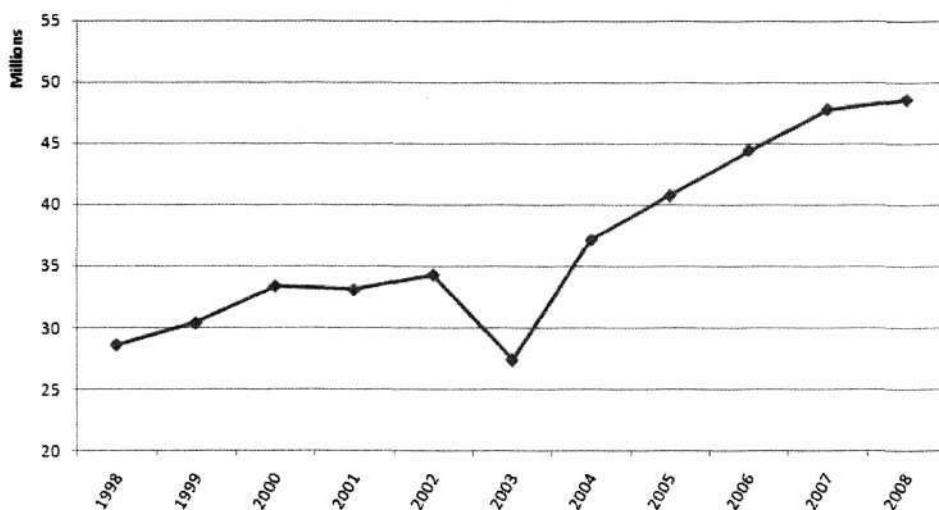


Figure AP- 5 HKG Airport Passenger Movements (ACI 2009)

HKG Airport Airfreight Statistics

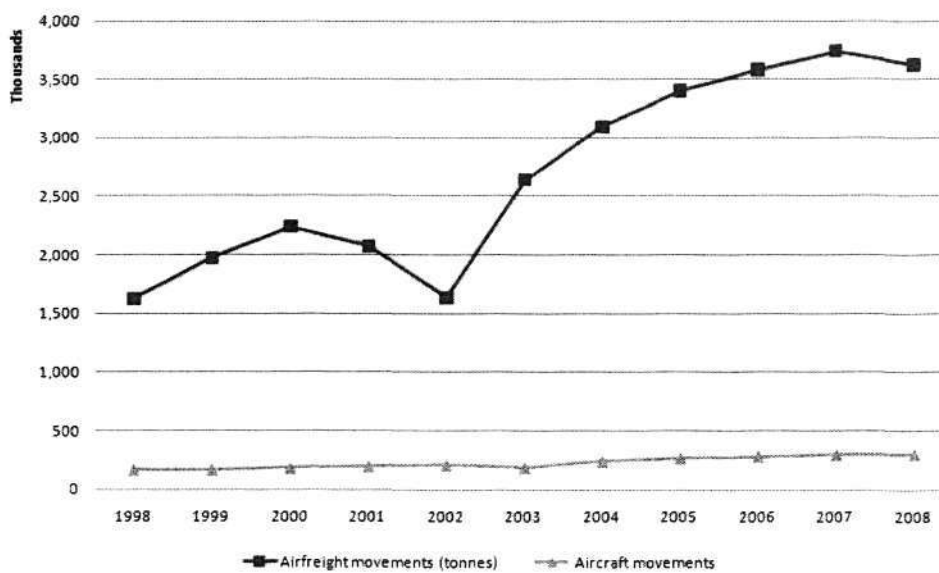


Figure AP- 6 HKG Airport Airfreight Statistics (ACI 2009)

Appendix D: Comparative Passenger Movement Chart

