Applications of Systems Thinking for Resilience Study in Maritime Transportation System of Systems

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Abstract - Maritime Transportation System (MTS) is a critical infrastructure system that enables economic activity through transferring goods between national and international destinations. This research is an effort to define and view MTS as a System of Systems (SoS) and apply Systems Thinking to understand, engineer, analyze, and govern it in a more effective and efficient way. We define Maritime Transportation System of Systems (MTSoS) as an integration of interdependent constituent systems and apply systemic tools such as Systemigrams to study critical properties of the system such as resilience and security through understanding its systemic interrelationships more effectively. A variety of systems engineering models have been applied to MTS. However, it is necessary to form a structured approach and develop new systemic toolsets that enables the stakeholders to view interdependencies and interconnections among the constituent systems of MTSoS.

Keywords: Maritime Transportation System of Systems; Systems Thinking; Systemigrams; Resilience.

1 Introduction

Maritime Transportation Systems (MTS) function in a socio-technological environment through a complex network of enterprises, each abiding by various sets of processes and interacting with a variety of physical infrastructure and myriad of equipment. Effective operation of MTS, which enables the transfer of goods and services between national and international destinations in a secure, safe, and profitable way, is essential for the economy of the country [1]. Acquiring such effectiveness necessitates the collaboration of many independent and active entities, each of which dynamically affects the other agents in the boundary of MTS, operates toward the common purpose of transportation, and interacts via many related procedures, while sharing lots of interconnected processes.

Such characteristic also brings about complexity into the realm of MTS. In Homeland Security Presidential Directive-13, “Maritime Domain” is defined as “all areas and things of, on, under, relating to, adjacent to, or bordering on a sea, ocean, or other navigable waterway, including all maritime-related activities, infrastructure, people, cargo, and vessels and other conveyances” [2]. This description alone reveals the level of complexity involved in the dynamics of maritime systems.

According to the literature, [3-5] each one of these active entities of MTS has the characteristics of a system and their collaboration in a collective community with a major purpose of its own, makes the entirety of MTS a System of Systems (SoS) [6, 7]. Components of MTS have operational and managerial independence; they are usually geographical or conceptual distributed; they enjoy evolutionary development processes to adapt with new technologies and regulations; and as a result, they all inherit emergent behaviors, which are mostly unexpected and sometimes even unknown to some extent.

Since MTS owns all major characteristics of a SoS, it consequently requires specific methodologies, tools, and techniques for governing its communication, interoperability. In fact, the complexity of relationships and interconnections among MTS constituents brings about a serious risk factor to the context of its service maintainability in face of disruptions and major adverse shocks to the system. Such a risk might make MTS ineffective in communication and responsiveness, which increases the vulnerability of SoS and as a result affects resiliency of the system. In order to avoid that, MTS must be designed and operated in such a manner that
create value out of togetherness of its constituent systems as opposed to make the structure of SoS a threat to service maintainability.

Many works have been done on systems design aspects of MTS, yet the idea of approaching such a complex maritime system from a SoS point of view is yet to be explored and developed. This paper is an effort to provide an insight to study MTS as a SoS, based on applications of Systems Thinking methodologies and its systemic tools. Utilization of such powerful toolset enables the stakeholders to address many issues of the system regarding important issues such as resilience and security.

2 Maritime Transportation System of Systems

Many enterprises participate within the boundaries of maritime systems. There are a lot of direct and indirect roles in MTS that are interrelated through a network of complicated rules, regulations, and business processes. The security issue is an example of MTS complicated process [8]. Even if we consider management of this single factor in American ports, it will be almost impossible to take all of the stemmed complexities into account. It has been a lot of efforts and investments dedicated to security related issues, however in reality, we are far away from calling our ports secured. According to Hultin et al., public American ports are exposed to all kinds of risks and even though a much greater security is provided by entities such as Custom’s Container Security Initiative (CSI) and Customs-Trade Partnership Against Terrorism (C-TPAT), only 2-3 % of the cargo entering to the U.S. is physically checked [9].

The organizational participants of MTS are autonomous. A wide range of organizations from civil society, governmental, and private sectors are involved in conducting MTS business. Figure 1 represents the hierarchical structure of MTS. These entities, which are all considered the stakeholders of MTS, have different perspectives. Yet as they perform in a hierarchy within their organization, they also interact with other entities in a network-centric level. Such characteristic extends MTS to a “network of maritime operations” [10] that can be described by the term “holarchy,” [11-13]. We have adopted the “holarchical view” to define Maritime Transportation System of Systems as a whole that embraces its autonomous constituent systems.

The constituents that form the complex network of maritime systems can be categorized in a variety of groups. However, from a systems perspective, we can identify them through their roles in overall performance of MTSoS. In this paper, we have chosen the classic categorization of major constituents that is available in the literature [10, 14-16], which defines them as: 1) ships; 2) ports; 3) intermodal connects; 4) waterways; and 5) users. Although these agents are a whole within their own boundaries and thus perform autonomously, they are also parts of the superior structure of MTSoS. Figure 2 represents the holarchical view to Maritime Transportation System of Systems.

Each one of MTSoS constituents is an independent operational system and includes several interdependent subsystems that work in hierarchy. If we go deeper in presenting MTSoS, it can be shown how entities of each layer are also connected.
horizontally. These interdependencies construct complexity in terms of communication as well as interoperability. The entities in charge of security exemplify interdependencies of MTSoS in lower layers. These agents include all the governmental as well as private agencies involved in the process of making ports safe [17]. From this perspective, security-related activities of MTSoS are shared among all five constituents. Thus, designing a resilient system is a function of understanding these interrelated activities.

3 Resilience of Maritime Transportation System of Systems

Maritime systems are always exposed to variety of organizational and environmental risks that may disrupt their services and potentially result in large amounts of direct and indirect financial losses [18]. These threats range from natural to man-made disasters [19]. Mansouri et al. categorize the roots of uncertainty in four major groups as: natural, organizational, technological, and human factors [20]. Since disruption as a result of uncertainty is inevitable, such systems need to be designed and operated in such a manner that they can adopt appropriate strategies such as flexibility, resilience, and agility in the face of disturbances.

Dictionaries commonly define “resilience” as the ability to “recover quickly from illness, change, or misfortune” [21]. While terms such as “buoyancy” or “a bouncing quality” are usually suggested as synonyms, resilience definitions generally refer to the ability of a material or a system, including an individual, a group, or an organization, to absorb change gracefully in the face of disruption and at the same time, keeping its core properties or functions to a certain level [22]. The term was proposed by Holling for the first time in the context of ecological research to distinguish between the system (ecosystem or society) that persists in a “state of equilibrium” or stability; and how dynamic systems behave in response to stress, when they move to instability from this equilibrium [23].

Resiliency in a SoS such as MTSoS, however, can be defined as a function of system’s vulnerability against potential disruption, and its adaptive capacity in recovering to an acceptable level of service within a reasonable timeframe after being affected [24-26]. As it is shown in Figure 3, setting controls for these two major factors is the only way to enhance resilience in a system and attain the favorable equilibrium.

In reality, MTSoS includes hundreds of entities, which are involved in conducting the system’s business from a wide scope of activities and functionalities. Maritime Transportation System of Systems includes a nexus of constituent systems, which are interrelated and surprisingly, their relationships generate some simple behavioral patterns. The integration of these constituent systems of autonomous entities that have bought into the boundary of a united organism to cooperate and collaborate, for individual and collective good and to deliver certain services has been called the Extended Enterprise by Boardman and Sauser [6].

Governmental, civil societies, and private sectors, each with a different perspective, are the stakeholders of MTSoS. The combination of these perspectives in itself is a constraint for the process of decision-making in Extended Enterprise level and it even sometimes brings about conflicts among the stakeholders. While governments of the countries involved in maritime transactions concentrate on matters such as national security, private sector businesses want to accelerate the flow of activities and the civil society sector is concerned about environmental issues, at the same time. These circumstances make the optimization process very challenging.

Complex Systems approach studies formation of relationships in a system in interaction with the environment and seeks to find out how these relationships between parts give rise to the collective behaviors of the system. Based on the categorization of the main disruptive causes into: natural, technological, organizational, and human factors [20], in this paper, we apply Systems Thinking methodologies to address resiliency of MTSoS by taking organizational and human factors into account. Systemigrams for example enable the stakeholders to understand the interconnections among constituent systems and provide them with appropriate input for analyzing the entire MTSoS.

Taking this complex, highly dynamic, and uncertain state of interrelations into account, MTSoS
has to be resilient. In other words, it must be capable of maintaining a certain level of serviceability in the face of adversities and disruptions. Therefore, it is necessary for the system to be able to plan proactively and prepare for effective and quick responses. This refers to the concept of adaptive capacity. A very important matter to consider is the fact that often, the resilience of one constituent system can cause imbalance for another one within the realm of MTSoS. To address this important issue, we have to move the notion of resilience to a higher level and try to think of and plan for it in terms of the resilient Maritime Transportation System of Systems. Our challenge would be to capture this notion in modeling the entire system and formulating the relationships and the challenge for the constituent systems is to collaboratively participate in designing and building “resilience” into the structure of MTSoS environment. We believe that Systemigrams can play a considerable role in this systemic multi-dimensional approach.

4 Systems Thinking Methodologies

The literature of systems theory states that all systems can be defined by their common characteristics such as: 1) system-environment boundary, 2) input, 3) output, 4) process, 5) state, 6) hierarchy, 7) goal-directedness, and 8) information [27]. We apply the same concept and use some systemic tools to formulate the problem in a way that help us find a better understanding about the nature of activities in Maritime Transportation System of Systems. Figure 4 for example, shows a summary of input, output, control, and mechanism of port operational system as a part of MTSoS.

While Figure 4 represents the port operational system, which is only one of MTSoS constituents, the scope of MTS as a SoS goes far beyond ports and in fact, includes all the activities of an extended supply chain that starts from manufacturers in the originating countries and ends up with retail stores at the destination. The idea of Systems Thinking suggests consideration of all the constituents of this extended supply chain for researching the behaviors of MTSoS as a whole. We define the boundary of the system to include all parts and nodes of such extended structure. We also propose the application of “Systemigrams,” which is an effective Systems Thinking tool devised by Boardman [6], to understand the structure of MTS in terms of interrelationship of its constituent systems.

The term “Systemigram” is derived from “Systemic Diagrams,” and has been used to “bring context to the meaning of togetherness” [6]. The stakeholders of MTSoS however, can use Systemigrams as a systemic tool that help them to learn about each other’s perspectives and to identify organizational and communicational bottlenecks of their interrelation. The result of such understanding will be more effective and efficient decision-makings. Systemigrams methodology, as applied here provide all MTSoS stakeholders with the right knowledge about the architectural structure of the extended network of activities in their environment and equip system analysts with relevant information on understanding systemic issues of such Extended Enterprise with consideration of resilience factors.

Having this kind of information about an Extended Enterprise is an essential for effective governance, security management, and resilience of that enterprise. Systemigrams provide stakeholders of the system with this understanding by representing the structure of the network via a storyboarding technique. A single Systemigram can be use as a representation of multiple networks [6]. Therefore, it will be the right tool to study the structure and operability of MTSoS.

The inclusion of multiple viewpoints, from multiple participants of a network, is generally important and valuable as it increases the richness of perspective in analysis. However, in the case of MTSoS it is essential to include knowledge and perspective of all the constituent systems in making decisions and adopting strategies regarding security or resiliency of the entire system. Systemigrams enable the stakeholders of MTSoS to explore diversity in their perspectives while maintaining a single objective, such as making a specific decision or adopting a resilience strategy, on which the
stakeholders can share thoughts and make a resolution.

Since, Systemigrams can be used as a powerful tool for capturing strategic intent of MTSoS, in a way that provides the stakeholders of the system with the common ground for communication and participation in decision-making, we have chosen them to be among our toolset for studying, evaluating, engineering, and governing certain characteristics of the system such as stability, security, resilience, and agility. We believe that this approach can also provide a foundation for architectural design and modification in MTSoS.

Based on all these considerations, we defined a project for our Systems Thinking class at School of Systems and Enterprises of Stevens Institute of Technology in which the students were supposed to approach the issues of security and resilience of MTSoS from a systemic point of view and by using Systemigrams.

In order to do that, we defined MTSoS as an extended supply chain between the countries of origin, where manufacturing process is done and the United States of America, where the manufactured products are distributed and consumed, as shown in Figure 5. Moreover, to make a more specific case, we chose the Port of Singapore as the point of origin and the Ports of Los Angeles and Long Beach (LA/LB) as destination points for the maritime transportation case in this learning exercise. The plan was to complete the Systemigrams gradually some tools and techniques of Systems Thinking were introduced to the students during the semester.

On the basis of this exercise, the students learned about the processes of maritime transportation in a System of Systems level and faced the challenges of making decisions and adopting strategies in a multi-layered, complex, and interconnected environments.

We allocated each one of these different pieces of the MTSoS extended supply chain to one or a group of graduate students. In better words, each student took the responsibility of each operational part as its major decision-maker. Therefore, all the participants of this class exercise were in fact a part of the whole system’s stakeholders. This provided everyone with the opportunity to understand the concept of participatory decision-making and learn the techniques of communication and collaboration in such Extended Enterprise environments.

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5 Conclusion

Maritime Transportation System of Systems are critical infrastructures that enable economic activities for a broad range of entities within a society, through transferring goods and passengers between national and international destinations in a safe, secure, and efficient way. Like any other infrastructural system that operates in a complex environment, MTSoS is exposed to a variety of disruptions.

While disturbances caused by environmental and technological factors are the output of natural disasters and/or technological malfunctions, hence usually not controllable by decision-makers of the system, many organizational and human factors, which are also often originated from systemic problems from inside, cause disruptions to the system that are manageable. Applying a Systems Thinking approach to the problem of MTSoS can empower the stakeholders to have a better understanding about the system they belong to and provides them with the knowledge and capability to resolve their issues in a systemic way.

Systemigrams in particular are strong tools that enable stakeholders of MTSoS to understand each other’s perspectives, organizational requirements, and strategies in a participatory environment and equip them with the appropriate toolset for designing resilience within the architectural structure of the entire system. Using Systemigrams brings context to the meaning of togetherness and broadens constituents’ knowledge to the SoS level in which satisfying systemic requirements of the whole is the main objective.

Acknowledgement

The authors of this article would like to thank doctoral students Camille Crichton-Summers and Mina Samaan from the School of Systems and Enterprises at Stevens Institute of Technology for sharing the outputs of their Systems Thinking class project.

References


