Responsible Design and Delivery of the Constructed Project
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A SYSTEM-OF-SYSTEMS FRAMEWORK FOR PUBLIC-PRIVATE PARTNERSHIP PROJECTS

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Public-private partnership projects are a complex form of megaprojects since they include a close-knit long-term contractual relationship between a public and private entity. Studying a PPP project as a monolithic system often leads to disregarding the emergent properties that occur from the interdependency between the subsystems. Hence there is a need for providing a framework for analyzing PPPs using the systems engineering approach. This paper proposes the adoption of a System-of-Systems (SoS) approach to analyzing PPP projects and proposes a framework for it. A top-down approach is used to identify the key components and their interrelationships. The analysis presented in this paper reveals the SoS taxonomy and lexicon for a PPP project and the hierarchical levels under it. The findings provide a step towards effectively analyzing the relationship within and across the various systems. They are expected to assist researchers in understanding and simulating the dynamics between the different subsystems.

Keywords: Systems engineering, Megaprojects, Taxonomy, Methodology.

1 INTRODUCTION

Public-private partnership projects have been in use for many types of projects such as roadways, water projects, and universities. They have many forms with combinations of build/operate/maintain/lease/transfer, but common among these diverse projects is their complexity and the multitude of parties involved (Khallaf *et al.* 2016). From this stems a need to understand and analyze PPPs using a systems engineering perspective. Systems engineering allows for integration of the multiple diverse systems and their interactions to better model them and ensure that their separate properties as well as combined effects are captured. Previous literature studied PPPs at one level, for example, project risk (Chung *et al.* 2010, Attarzadeh *et al.* 2011, Li *et al.* 2017), project bidding (Jang 2010, Ho 2009) or success/failure factors (Abdul-aziz and Kassem 2011, Liu *et al.* 2015) but did not consider the different systems and their interdependencies thus failing to realize the non-monolithic nature of PPPs. Hence this paper uses the single level studied as a point of departure to propose a framework for PPPs by studying them as a complex SoS. This will guide in the PPP design and help achieve synergy among its subsystems.

This systems engineering approach has been applied mainly to the aerospace and defense industries but has also spread to healthcare, transportation, and other industries. In the context of SoS applications in civil engineering, several studies applied the SoS technique to model and simulate topics under infrastructure projects. Some of the previous applications of SoS in civil engineering have been to model project performance (Zhu and Mostafavi 2014), plan national infrastructure (Otto *et al.* 2016), and propose megaproject systems integration (Zhu *et al.* 2017). However, to the authors' knowledge, no previous studies have looked into how PPPs can be studied and modeled as a SoS.

2 PUBLIC-PRIVATE PARTNERSHIP AS A SYSTEM-OF-SYSTEMS

2.1 System-of-Systems (SoS)

A system-of-systems can be defined as a complex large-scale system consisting of autonomous subsystems with diverse frameworks under it. These subsystems work independently but also interact in order to deliver the needed service (DeLaurentis and Crossley 2005). SoSs have common characteristics such as operational and managerial independence and the manifestation of emergent properties from the internal complexity emanating from their interactions. A SoS's components must also have a common objective or purpose, which in the case of PPPs is the delivery of a service. PPPs can be considered a collaborative SoS because the components work together for the common goal of service delivery. Similar to national transportation systems (DeLaurentis and Callaway 2004), PPPs are considered complex because of the heterogeneity of their subsystems, the physically-dispersed systems, and uncertainty of the conditions. One of the important challenges facing megaprojects and SoSs is systems integration and studying interactions among systems (DeLaurentis and Crossley 2005 and Zhu *et al.* 2017).

2.2 SoS Traits

Public-private partnerships are commonly used for the delivery of megaprojects. These projects are composed of multiple systems working together for a common goal, the delivery of a service. The growing application of PPPs along with the failures that have occurred in some of them enforces that there is a current issue facing PPPs that needs to be studied. Studying a PPP as a monolithic system leads to the neglecting of a PPP's emergent properties. According to DeLaurentis and Crossley (2005), there is a need to identify SoS examples and create a taxonomy of SoS types to solve these problems.

According to Maier (1998), there are five traits of a SoS: operational independence (each entity in a PPP such as the public/private entity is autonomous in its operations), managerial independence (each entity has its own hierarchy of management), evolutionary development (transition toward wireless technology and cloud storage of data), emergent behavior (interaction between the entities), and geographical distribution (the entities/services are not located in the same area). A SoS generally has three characteristic dimensions: type, control, and connectivity of systems (DeLaurentis *et al.* 2011). In a PPP, the system type is neither wholly technological nor wholly human; instead it is a hybrid of both types, since it depends on people and technology to deliver the service. In general, a PPP has a high level of control and is not controlled by any authority; on the other hand, it is governed by the contract between the public and private entities. So the concessionaire would have power in this case that emerges from its contractual relationship with the public entity. Finally, the connectivity of systems under a PPP leads to the presence of emergent behavior. This emergent behavior can arise from the dynamics between the public and private parties as well as from external non-contractual entities. It can also arise due to the interdependency between a PPP's subsystems.

2.3 Top Down Approach

A top-down approach is applied in this paper to view the PPP holistically and identify its components and how they interact. Systems engineering introduced this concept to optimize an entire system rather than optimize its components separately (Ender 2006). This top-down approach helps transform high-level needs and requirements to lower-level processes that are planned, managed, and tracked more easily and efficiently. Functional decomposition is performed on the SoS to reach the lower level components (Ender 2006). Similar to megaprojects, a PPP project can be decomposed into its socio-technical constituents (Bygstad 2010). The social component includes the interaction between the parties involved whether contractual or not, and the technical component is the service to be provided or project to be built.

2.4 Abstraction and Taxonomy

Abstraction of the PPP is needed to explore the systems and emergent properties. SoS is used to analyze the relationship between systems and to suggest problem-solving techniques (Jackson 1990). The lexicon categories in a SoS are: resources, operations, policy, and economics. Resources are the physical entities that manifest in the SoS; operations are the processes that guide the movement of the resources; economics are the non-physical financial-related aspects that guide the resources of the SoS; and finally policies are the guidelines/procedures that guide the activity of the entities (DeLaurentis and Crossley 2005). According to Mostafavi *et al.* (2014), effective policies are needed for the expansion of infrastructure projects. In the United States, some states have developed policies for PPP projects such as Virginia and California, and thus have a higher number of PPP projects than other states like Montana and Wyoming that do not have PPP-enabling legislation. Table 1 shows the hierarchical classification of the lexicon under three distinct hierarchical levels. These three levels (project, market, and macro) are adapted from Khallaf (2016) based on the proposed risk classification. Within each of these categories is a hierarchy of subsystems. The lowest level under a resource, α, would be an individual entity, which then aggregates to the next level, β, which finally aggregates to the highest level γ (an aggregation of β). The level of aggregation chosen for an analysis would depend on what is to be studied. For example, if the level of focus were on a specific PPP project to study the effect of the policies and economics on it, the project (α) level would be chosen and the lexicon identified for that level only. Computational models can be used to simulate these interactions and show their effects.

Table 1. PPP project ROPE.

Level	Resources	Operations	Policy	Economics
α Project	Project resources	Activities for operating a project	Policies relating to a single PPP project (by the public or private entity)	Economics of constructing/operating a single resource for a PPP project
β Market	Resources in a market	Activities for operating a project at a market level	Policies relating to multiple resource use for PPP projects (by the state/country)	Economics of constructing/operating resource networks for PPP projects
γ Macro	Global resources	Activities for operating a project at a global level	Policies relating to the global PPP projects (by global entities)	Economics at a global level

Under the abstraction phase the entities and their roles are identified within a system. Figure 1 shows the entities involved in a PPP project at the base level (α). They are classified into two categories based on their power and influence on a project: endogenous vs. exogenous and explicit vs. implicit. Explicit entities are those that manifest physically while implicit entities are usually implied. Exogenous entities are found outside the system while endogenous entities are internal within the system. The stakeholder group consists of entities that can affect or can be affected by the project including the users, concessionaire, owner, politicians, and media. Disruptors have a negative impact on the project such as financial issues or resource delay or unavailability. Drivers include advancements or policies made within a project to enable its success. The entities can also be identified and mapped out for the market level (e.g. stable market conditions (drivers), competitors (disruptors)) as well as for the global level (e.g. policies enabling PPP projects (drivers).

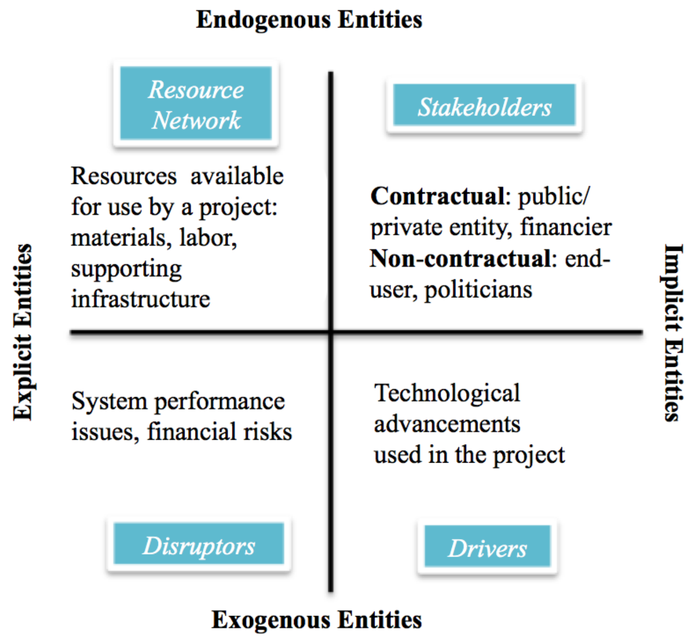

Figure 1. System-of-systems entities in a PPP project at the base level.

Figure 2 shows the policies and economics in a PPP project for the three hierarchical levels (macro, market, and project) based on the classification by Khallaf (2016). Although each level has its own policies, the lower level policies can be affected by the higher-lever policies. Examples of policies in a country are conditions for which to bail out a concession. The concession toll road program that started in the beginning of the 1990s in Mexico was bailed out by the government in 1997 with an approximate cost of 1 to 1.7 per cent of GDP (Guasch *et al.* 2007). Three out of four projects awarded in France in the 1970s went bankrupt and were rescued by the government (Guasch 2003). A mixed-use building at the University of Quebec at Montreal was $200 million over budget, which doubled its cost to a total of $400 million (Sanger and Crawley 2009). The high cost and dire consequences from PPP failure have driven the need for studying PPPs.

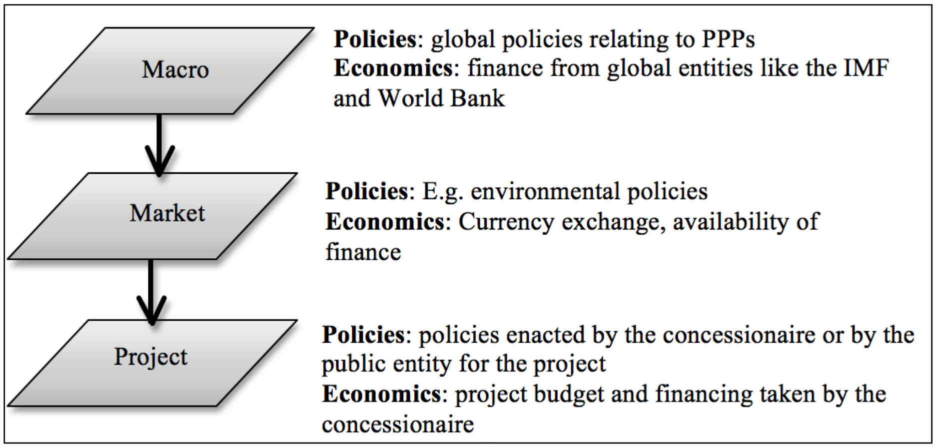

Figure 2. Policies and economics under the three hierarchical levels

3 CONCLUSION

This paper presented an integrated framework for PPP projects as a system-of-systems. A top-down approach was used to identify the hierarchical levels and the resources, operations, policies, and economics under each level. Based on the SoS classification, the three hierarchical levels identified are macro, market, and project. The first step in the proposed framework is identifying the resources, operations, policies, and economics (Table 1) followed by identifying the level of analysis (α, β, γ). Based on the level chosen, the entities (endogenous/exogenous and explicit/implicit) can then be identified and mapped as shown in Figure 1. The interrelationships between the hierarchical levels can also be identified (Figure 2) to show the cascading effects between them. This framework can be used to model the intra-level relationships such as the dynamics between the hierarchical levels or the inter-level relationships such as those between the different subsystems (under one level). Using the systems engineering approach also enables the design of the subsystems themselves. PPPs need to be designed effectively and operated both as separate autonomous systems and also as interconnected systems to capture the emergent dynamics from their interactions. Connecting the distinct and dissimilar systems together through SoS enables the modeling and discovery of vulnerabilities in a system. This will help in the conceptual phase of system design by minimizing vulnerabilities and maximizing systems connections. DeLaurentis and Crossley (2005) suggest that underperformances in complex SoS are the result of inadequate attention to the interaction among the subsystems. This can be solved by following the framework for PPP SoS and taking into consideration the emergent dynamics that occur from the systems.

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