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Systems Engineering to transform the governance in complex project environments

ABSTRACT

Projects delivered in complex environments are often late, over-budget and provide fewer benefits than what originally expected. Systems Engineering is the emerging paradigm in complex project environments to transform the governance from "project based" to "system based" and thereby increase the chance of holistic success. Systems Engineering is a multidisciplinary approach to enable the successful delivery of systems in complex environments through a comprehensive set of approaches, techniques and tools, initially developed in the USA after the Second World War. This paper focuses on how Systems Engineering can transform the governance from "project governance" to "system governance", improving the performance of projects delivered in a complex environment. The paper presents Systems Engineering tools and techniques focusing, in particular, on the most relevant for the project management, project governance and stakeholders' management. At the end it provides a rich research agenda for further studies.

Keywords: Systems Engineering; Project Governance; Complex Project Environments; Transforming Governance.

1 Introduction

1.1 Defining project success with the Systems Engineering perspective

Systems Engineering (SE) is a discipline developed to deliver successful projects (and systems) in complex environments (INCOSE, 2010). The definition of success is quite different from the historically first definitions based on "cost, time and quality" (the so called iron-triangle). According to the iron-triangle, a project (e.g. building an airport) was considered a success if the project manager was able to deliver it respecting time and budget constraints as well as the customer's specifications written in the contract. While many practitioners, in particular project managers of small organisations working on small projects, still agree and adopt this definition, the literature and large organisations working in complex project environments have moved away. For instance (Atkinson, 1999) presents an organic view of another three sets of success criteria in addition to the iron-triangle: the information system, benefits for the organisation and benefits for the stakeholders' community. In other words the airport, once completed, should make people travel quite smoothly.

Terminal 5 at London Heathrow airport was a project delivered on time and budget, with all the physical and electronic infrastructures built according to the specifications. Nevertheless, because of the imperfect commissioning, integration and untrained workforce, once opened, the systems immediately collapsed, with thousands of bags failing to travel with their owners, and over hundreds of flights cancelled. It took months to recover the situation and achieve smooth operation (Davies et al., 2009). *"The surgery was a success, but the patient died"* is an old adage similar in many languages and cultures. It is an analogy presenting the difference between a successful process (the surgery perfectly performed – the airport perfectly built) and the achievement of the final result (to recover the patient – to have people traveling).

There is still a lot of confusion about this difference. (Ika, 2009) in his paper reviewing the definition of project success stressed this point, elaborating the idea of (Shenhar & Dvir, 1996) *"In our journey toward a comprehensive understanding of project success, one should not confuse any* *more between project management success and project success. Semantically, project management success refers to efficiency, an internal concern to the project team, and project success embraces concerns for efficiency and effectiveness—in other words, all concerns, whether internal or external, short-term or long-term".*

(Aaron et al., 2001) present four major distinct success dimensions: (1) project efficiency, (2) impact on the customer, (3) direct business and organizational success, and (4) preparing for the future. They stress the importance of using these success dimensions to tailor the definition of project success according to the characteristics of the project itself. These ideas are further elaborated by (Han et al., 2012) presenting a taxonomy of project success according to project life cycle, success category, macro-dimensions and micro-dimensions. It presents a clear long term view of benefits, both for the organisation and its customers, including: *"fulfilling customer's needs, Customer is using product & expresses satisfaction; Immediate revenue and profits enhanced, Larger market share generated, Will create new opportunities for future, will position customer competitively etc."* .

SE is exactly the discipline developed in the last 60 years to enable the delivering of successful projects in complex project environments according to this broad view. SE is strongly focused on the Project Governance (PG), which is the key factor to achieve project success (Müller, 2009).

1.2 Project governance and project success

A recent report (Project Management Solutions, 2011) states that 37% of projects fail. For other authors the number is even higher, e.g. (Morris, 2008) reports as between 60% and 82% of projects fail. (Cantarelli et al., 2012) relaying on a database composed by 806 large projects delivered worldwide have an average cost overrun of 35.5% and very heterogeneous performance (standard deviation 56.3%). Moreover once completed the projects provide fewer benefits than expected, e.g. (Flyvbjerg, 2006) shows that in transportation projects rail passenger forecasts is -51.4%, with 84% of all rail projects being wrong by more than ±20%. For roads, average inaccuracy in traffic forecasts is 9.5%, with half of all road forecasts being wrong by more than ±20%. Considered the definitions of project success previously provided, it makes sense to ask "Why projects fail?".

A major contribution to understanding the reasons for cost and time escalation as well as poor benefits delivered in complex project environments has to be acknowledged to Flyvbjerg and Van Marrewijk. In particular Flyvbjerg (Flyvbjerg et al., 2003) claims that project organization and its governance (see section 2.1) are responsible for cost overruns, delays in schedules and poor benefits. In his work ((Flyvbjerg, 2006) and (Flyvbjerg, 2012)) Flyvbjerg explains that the PG makes projects fail because of two sets of reasons: (1) Psychological-Optimism bias and (2) Political-economic: Strategic misinterpretation, rent-seeking behaviour, misaligned incentives. He proposes a methodology called "reference class forecast" to improve the quality of estimations.

Focusing on governance and complexity Van Marrewijk, (Van Marrewijk, 2005) (Van Marrewijk et al., 2008) argues that project failures are caused by (1) uncertainty in the way projects must be governed, (2) scope ambiguity (3) technical complexity and (4) involvement of a large number of partners with different cultures and different ways of work. According to the author, it is possible to improve project performance with a better PG and a better definition of the responsibilities of the key stakeholders involved. In particular, he refers to the so called "control versus commitment dilemma". When the project organization exercises dominant control, the partners lose micro-management commitment to the project. They feel that they do not have autonomy to make decisions and consider their role focused only on accomplishing tasks they are put in charge of. However commitment is fundamental in order to achieve success, so it is necessary to find an optimal compromise between control and freedom.

Many projects delivered in complex environments are characterized by a high degree of uncertainty, as well as a mixture of jointed organizations and sub-contracting. It is impossible to control all phases and all single elements of the project with a strictly hierarchical method. In complex project environments, the partners are heavily involved in decision making since they have specific competencies essential for the project execution; this increases the complexity in delivering the project (Van Marrewijk, 2004). (Van Marrewijk et al., 2008) suggests that further studies should be focused in this direction, since the optimal form of governance has not yet been identified.

In conclusion, Van Marrewijk and Flyvbjerg agree that poor project performance is mainly due to poor project planning and poor project initiation. However regarding how to cope with this issue Van Marrewijk has a quite different view to that of Flyvbjerg. Flyvbjerg suggests a unique project organization, which control strongly most of the activities, whereas Van Marrewijk supports resolving the "control versus commitment dilemma".

1.3 Systems Engineering to transform the governance in complex projects environments

As seen in the previous section, even today, despite the progress of project management (PM) tools and techniques, many projects still register poor performance. Underperforming projects are often delivered in a project environment characterised by:

1. rapid changes of technologies; shortened technology cycle time; increased risks of obsolescence (Hanratty et al., 2002);
2. increasingly interoperable and interdependence systems (Jaafari, 2003);
3. emphasis on cost reduction, with tight schedules and without quality or scope reduction (Laufer et al., 1996);
4. integration issue: high number of system parts and organizations involved (Calvano & John, 2004) (Locatelli & Mancini, 2010);
5. combining multiple technical disciplines (Ryan & Faulconbridge, 2005);
6. competitive pressures (Kossiakoff et al., 2011).

These 6 elements are typical in complex project environments. With this background and the guidelines of (GAPPS, 2007) we define as "complex" a project environment with at least one of the following characteristics:

- several key distinct disciplines, methods, or approaches involved in performing the project;

- strong legal, social, or environmental implications from performing the project;
- usage of most of partner's resources (both tangible and intangible);
- strategic importance of the project to the organisation or organisations involved;
- stakeholders with conflicting needs regarding the characteristics of the product of the project and
- high number and variety of interfaces between the project and other organisational entities.

SE is a multidisciplinary approach and means to enable the realization of successful systems in complex environments (INCOSE, 2010). It achieves this goal by defining customers' needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. SE considers both the business and the technical needs of all stakeholders with the goal of providing a quality product that meets the user needs. SE provides the competencies required for successful project management i.e. *"shared leadership; social competence and emotional intelligence; communication; skills in organizational politics; and the importance of visions, values, and beliefs have emerged as competencies that are required from project managers in complex environments"* (Janice & Mengel, 2008).

The modern origins of SE can be traced to the 1930's, but the first significant developments were in the early '50s when the US DoD[1] needed to deliver (military) projects respecting time, budget, quality and these critical aspects:

1. able to accomplish long term goals;
2. with a strong strategic management of stakeholders (suppliers and final users).

[1] The Department of Defense (DoD) is the Executive Department of the Government of the United States of America charged with coordinating and supervising all agencies and functions of the government concerned directly with national security and the United States Armed Forces. Several management practices and tools, like the SE, used today in military and civil environment can be tracked back to technique developed by the DoD.

It was not enough to deliver a project/system (e.g. an aircraft) within time and with the performance required, but was necessary to deliver it considering the whole set of correlated aspects: pilot training, aircraft carriers, maintenance in distant countries, etc., with the long term view of keeping the aircraft "flexible" to accept with few modifications new weapons or be used with different aircraft carriers in different missions. To accomplish this result in such complex environments the PG with a project view was no longer enough. In such complex project environments, SE was necessary to shift from "project governance" to "system governance".

System governance increases the likelihood of project success. In fact, despite many project failures, the literature also presents successful projects delivered in complex environments: the metro extension in the Rotterdam Region (Giezen, 2012); the bridge linking the Oresund Region i.e. the eastern Denmark and southern Sweden Bridge (INCOSE, 2006); NASA projects such as Mars Pathfinder (Nicholas & Steyn, 2008). A shared characteristic of these projects is the application of principles and practices which can be traced back to SE. Therefore, given the relevance of SE for projects delivered in complex environments, this paper aims to explain how SE can improve project performance by transforming the governance from "Project governance" to "System governance".

Under this new perspective, The West Coast Route Modernization (WCRM) project is an emblematic example, both of non-application (in the early phase), and application (in later phases) of SE in a complex project environment as presented in (Pyster et al., 2012). The West Coast Main Line is a principal United Kingdom (UK) railway artery serving London, the Midlands, the North West and Scotland. In 1998, the British government embarked on a modernization program called WCRM project. The scope of the project included the reparation of sections of railway seriously dilapidated and the general improvement of the whole infrastructure since the new high speed trains required a complete overhaul of signalling, power supply and switching systems. Early on, the WCRM upgrade had serious problems. A major complicating factor was the introduction of a new signalling technology that was designed to allow improved services for new trains running at

140 miles per hour. By 2001, neither the rail infrastructure upgrade nor the new trains were on course for delivery as expected in the 1998 agreement. By May 2002 the projection of the program's final cost had risen from £2.5 billion (in 1998) to £14.5 billion, but had delivered only a sixth of the original scope. Poor management of contracts added to costs. In order to remedy the situation, the SRA initiated the following actions, which align with generally accepted systems engineering (SE) practice:

- a straightforward direction for the project was developed and documented specifying desired goals and outcomes;
- a well-defined, measurable set of program outputs was established, along with more detailed infrastructure requirements, which were then subject to systematic change control and monitoring procedures fixing scope. Contractors were invited to tender to complete detailed designs and deliver the work to a fixed price;
- a clear program governance structures were instituted and
- the SRA consulted widely with stakeholders and in turn, kept stakeholders informed.

The new arrangements worked well and that there were benefits to this approach including enabling the program to identify opportunities to reduce the total cost by over £4 billion.

This case exhibits (1) that the misapplication of SE principles and practices can lead to many problems and (2) that when SE is rightly applied such problems can be solved.

This paper has been divided into four parts. The first part summarises the most relevant literature about the two key elements: PG in Complex Project Environments and SE. The second part firstly focuses on SE approaches for the PG and secondly on SE Techniques and tools. The aim is to provide the reader with the key aspects to understand and implement SE. The third section discusses the interrelationships between the elements of SE and PG. The goal of this section is to bring together all the elements previously discussed to provide a holistic overview. The fourth section summarises the key aspects and provides a research agenda.

2 Literature Review: Project Governance and Systems Engineering

The literature review focuses on the two main elements of this investigation: (1) PG in complex projects environments and (2) SE. The first aim is to understand the peculiar aspects of PG in complex project environments and its impacts on project performance. The second aim is to understand what is SE and investigate how SE can transform the governance from a "project based governance" to a "system based governance".

2.1 Project Governance in Complex Project Environments

According to (Müller, 2009) the PG is the *"value system, responsibilities, processes and policies that allow projects to achieve organizational objectives and foster implementation that is in the best interests of all the stakeholders, internal and external, and the corporation itself".*

PG is a quite recent concept. Its systematic investigation can trace its roots back to (Reve & Levitt, 1984) describing the trilateral governance arrangements involving a client, a consultant and a contractor and highlighting different types of relationships among large project stakeholders. (Miller & Lessard, 2001a) (Miller & Lessard, 2001b) explain that the organizational structure of a project, the shaping of the project, the project's institutional framework and the capacity of self-regulation are essential features of governance.

(Floricel & Miller, 2001) introduce the concept of governability, referring to a group of properties, including cohesion, resources, flexibility, and governability, enabling a project to react to unexpected events occurring during its life cycle.

(Winch, 2001) presents a conceptual framework to analyse PG across the project's life cycle.

(Turner & Keegan, 2001) discuss the governance structures adopted by successful project-based organizations and argue that the governance structure of the project should take into account whether few large projects, or many small projects are undertaken, and whether projects are developed by a few, large dominant clients or by many small clients. In addition they introduce the role of a broker and the role of a steward to support efficient and effective governance of projects within a firm's organization.

(Winch, 2006) provides an enlarged view of governance from the "Pure contractual form" to a *"in this broader context of institutions and behaviour by defining it as the governance level mediating between the institutional level and the behavioural level. Through this mediation, governance choices by firms are both structured by the institutional context and shape that context over time. Similarly, individual behaviours and values are both influenced by the choice of governance mode and influence that choice"*.

(Müller, 2009) is a milestone work in the field of PG. It discusses governance at project level and at organization level suggesting a model linking governance at different project levels i.e. project management, program management and strategic management.

(Ruuska et al., 2011) and (Locatelli & Mancini, 2012a) analyse two projects, both affected by "time and cost escalations", based on the same technology (the EPR nuclear reactor) but carried out by different stakeholders with very different linkages among them. They demonstrate that these elements are tightly connected since most of the time and cost escalation can be explained by the PG. They stress how the PG is a key aspect to explain the project performance.

In conclusion the key aspects of the PG presented in the literature are:

- PG is a relatively new field of analysis, further research is needed;
- PG is relevant for the project success, in particular for large projects and projects performed in complex environment;

The PG described in (Müller, 2009) can be considered the state of the art. It has the point of view of a Corporation and its "board of directors", interested in governing a project with the goal of optimising its strategic objectives consistently with programme and portfolio (see the discussion on Project governance hierarchy). This view is probably adequate for projects delivered in non-complex environments. In this case the corporation has a deep understanding of the project scope as well as the technologies, the stakeholders and the risks involved. However for projects delivered in complex environments the governance needs to be transformed by "corporation/project perspective" to "system perspective". As explained in the next section, SE is the methodology to achieve this transformation. By leveraging on SE we aim to argue that in complex environment, besides the "vertical view" of (Müller, 2009), the PG need a broader view, that lasting more than the project team and the duration of the project itself. As in the emblematic example of the governances of building nuclear power plants described in (Ruuska et al., 2011) there is a need to include in the PG the large set of key stakeholders (e.g. the nuclear safety authority and the customer) addressing together (for instance with the IPT presented in section 3.2.1) the key project aspects to deliver a "project designed for the operations". In complex project environments, the vertical PG can be a starting point but is not enough.

2.2 System Engineering as support for the Project Governance

SE is the discipline established after the Second World War for governing the development of military and aerospace projects. A detailed analysis of the technical and managerial documents related to SE (from its origins to the actual configuration), allowed the definition of a synthetic time line of its development (see Figure 1).

PLACE Figure 1 HERE

Figure 1 SE origins Timeline

In (INCOSE, 2010) it is possible to find some significant examples of SE application: "Nike Project", the line-of-sight anti-aircraft missile system supported by Bell Labs (1945-1953); SAGE (Semi-Automatic Ground Environment) Air Defense system defined and managed by Massachusetts Institute of Technology (MIT) (1951-1980); ATLAS Intercontinental Ballistic Missile Program (1954-1964); and the Apollo Project (INCOSE, 2000). It is rather difficult to provide a single definition of SE since the literature provides several different definitions, even if the most common and accepted is (INCOSE, 2006) *"SE is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and* *system validation while considering the complete problem. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs."*

The project that SE governs has a hierarchical nature with the system divided into subsystems. The subsystems can be hardware, software, firmware, personnel, facilities, data, materials, services, and processes (ANSI/EIA 632, 1999). SE assures that the interactions and interfaces between them are compatible (DoD, 2001). Even if SE is an iterative and recursive multidisciplinary approach able to govern each stage of system's life cycle (ISO/IEC 15288:2008, 2008), the main benefits are at the earlier project stages (NASA, 1995). These stages are the project definition (scope management), project stakeholder management and project planning (all aspects related to the PG). So SE is particularly valuable in complex project environments as defined in section 1.3.

Many authors have analysed the Value of SE on PG, highlighting that it has a positive impact on the project performance (Table 1).

INSERT Table 1 HERE

Table 1 Impact of SE

2.2.1 SE Standards

As emerged in Figure 1 a relevant topic in SE are its "standards". SE standards are a formalized collection of glossary, tools and techniques. (DOD, 1969) is the first standard of the U.S. DoD delivered in 1969 to manage the defense acquisition programs. The proven usefulness of this approach caused the DoD to develop several improved standards in the following years. The objective was to create a common terminology to facilitate communication and to involve the key stakeholders in the PG from the tendering phase verifying that each of them strictly acts according to the contract. During the following years, a variety of SE standards have been issued (Figure 2), evolving from the U.S. Military to international and commercial scope. The three SE standards now available and used commonly are (ANSI/EIA-632, 2003), (IEEE, 2005) and (ISO/IEC 15288:2008, 2008).

(ANSI/EIA-632, 2003) focuses on the PG of the early stages of a system's life cycle. It describes SE "processes" and their relationships for the application.

(IEEE, 2005) focuses on the PG of the "development stage" of a generic system. This is a crucial point in each project since the final result (physical output and stakeholders' definitions) is the last step of progressive elaborations. (IEEE, 2005) provides also the most detailed SE processes.

(ISO/IEC 15288:2008, 2008) provides a general view of the entire life cycle of a system and describes SE processes with the highest level of abstraction.

PLACE Figure 2 HERE

Figure 2 SE Standards Timeline

2.2.2 System Engineering Vs. Project management

There are many overlaps between SE and other disciplines, in particular PM.

(Eisner, 1997) discusses in detail the critical relationships and interconnections between PM and SE. According to (Sharon et al., 2011) SE includes technical issues that relate to the "system" governance while PM includes managerial issues that relate to the "project" governance. (Forsberg et al., 2005) identifies an overlap between SE and PM governance in requirements management i.e. the management of the project business, budget and technical baselines. (Pyster et al., 2012) discuss two alternative governance strategies: if the project is schedule-driven, the Systems Engineer may occupy a staff position subordinate to the Project Manager. However if the project is requirements-driven, the Systems Engineer may provide the authoritative interface to the customer with the Project Manager as staff.

Shortly SE is a multidisciplinary approach covering both technical and managerial aspects. The technical concern is based on the "System", which has substantial technical components. SE also has a management concern, addressing the governance of the technical work (Ferris, 2008). This concern is seen in the inclusion in SE of processes to manage the projects (INCOSE, 2006). SE merges traditional technical and managerial disciplines into a holistic system approach.

2.2.3 Successful projects in complex environments

Most of the successful projects in complex environments have applied certain principles and practices which can be traced back to SE. Beside the examples presented in section 1.3, the most famous and best investigated project developed according to SE is the International Space Station. The International Space Station is a laboratory in space in which the astronauts conduct experiments in near-zero gravity, or “microgravity” (Smith, 2003). This project is the result of the combined effort of 5 aerospace agencies from 15 countries (NASA, 1999). In a short period of time, NASA (the leading organisation) and its partners found how to coordinate and integrate all of the international partners and their highly interconnected modules, different cultures, technical languages and operational perspectives on risks and safety. At the same time NASA had to cope with issues related to technical obsolescence, logistics, technology gaps and significant career progression of its personnel. NASA had to develop expertise in supporting its SE approach while adjusting to the realities of a complex external environment including international politics across many partner nations.

SE governance requires more effort in the early stages of the project life cycle. It is essential to achieve a clear definition of objectives, roles, responsibilities and requirements (SRA, 2003). For instance in the West Coast Route Modernization a new documentation approach was introduced to foster readability, using a simple and concise language with unique identifiers and traceability (Loubersac & Halliday, 2003). SE governance requires the strong involvement of all stakeholders during the entire project.

3 How SE can improve the project governance

SE is based on a set of high level approaches and practically implemented with a set of techniques and tool. The goal of this section is to define and briefly discuss these approaches (section 3.1) and to present a selection of all the various techniques and tools (section 3.2). Tools and techniques listed and discussed in this section are those to support the governance of projects delivered in complex environments, for more information they are described with all the necessary details in SE standards (see section 2.2.1). Figure 3 provides a general overview. In the next section all these elements will be brought together in a holistic view (Figure 3).

PLESE INSERT Figure 3 HERE

Figure 3 The elements of SE that impact on Project Governance

3.1 SE Approaches

3.1.1 Systems Thinking

Systems Thinking is the method developed to understand and analyse how different correlated elements, regarded as systems, influence one another within a whole (Jackson, 2003). Systems Thinking aims to complement reductionism with expansionism; analysis with synthesis; cause and effect thinking with circular cause and effect; and complements determinism with indeterminism (Pourdehnad, 2007).

For example in an air transport system it is necessary to consider the system elements (such as the commercial air transport system) but also the system of which it is part of (such as the worldwide aviation system) and the region where it is localised. (Checkland, 2012) explains that Systems Thinking is required, especially in complex environments, since the focus should not be on the sub-system, but on the system as a whole. *"What in the end justifies systems thinking is the fact that any whole has properties—the so-called emergent properties—that exist only in relation to the complete whole. [….] the whole is more than the sum of its parts".*

According to (Jenkins, 1972) the governance based on Systems Thinking is able to:

1. address the increasing complexity of projects;
2. look at entirely different problems coming from various areas of technology and business emphasizing their common features when combined in systems;
3. exert a unifying influence on governance by linking together the many specialist techniques needed to solve complex problems;
4. require changes in the way that both individuals and organizations work.

In particular, Systems Thinking requires that problem solving is carried out on a more multidisciplinary basis to involve in SE governance stakeholders with a widely large set of skills and expertise. Systems Thinking successfully contributes to the governance of innovativeness, complexity and uncertainty by embedding flexibility in managerial activities (Kapsali, 2011).

(Checkland, 2000) identifies two fundamental forms of Systems Thinking: hard and soft.

SE described as hard Systems Thinking is the "Traditional SE". Historically the SE discipline was primarily aimed at developing, modifying or supporting hard systems, as the first weapons of the USA DoD. Hard Systems Thinking is ideal to cope with well-defined projects with reliable data, clear objectives and systems that can be optimized by classical engineering methodologies. Typical examples of these projects are: optimizing the output of an already operating chemical plant, optimise usage of resources in a hospital, building a "standard house" in an urbanised area.

Soft Systems Thinking is ideal to cope with problems involving incomplete data, unclear goals, human beings and cultural considerations. It is based on using a "learning system", focusing on communication, inter-subjective complexity and interpretations. It rejects the idea of a single project solution and considers situations as problematic because they contain multiple world-views, with their own perception, experience and multiple objectives changing over the time. Typical examples of these projects are the International Space Station or a new technology of a nuclear power plant where there are several stakeholders with different cultures and conflicting interests or, for small projects, the coding of software to address new niche markets, developing a radically new product. In this context, the term systemic describes the process of inquiry, which guides the understanding of the challenge. Soft Systems Thinking is a learning system aimed at 'action to improve' situations in complex environment.

Today, the SE perspective is based on both forms of Systems Thinking (INCOSE, 2006). In order to address increasingly environment complexity INCOSE supports the activities of the *Complex Systems Working Group*. Leveraging on both forms of ST it investigates Complex Systems Science, such as chaos, complexity, complex adaptive systems, nonlinear static and dynamics, social science, power laws, ecology, and others. Its aim is to increase the knowledge of complex systems in order to improve the application of SE in complex environments.

3.1.2 Open Systems Approach & Modular design

The Open Systems approach is a methodology that continuously interacts with its environment or surroundings, adapting and evolving requirements throughout the system's life to cope with changes and new requirements (DoD, 2002).

According to (Hanratty et al., 2002) "closed systems" are unique in their designs, requiring unique equipment to support them and supported by a single or limited set of suppliers. Closed Systems are unique "white elephants", being both difficult and costly to support. Conversely, Open Systems can be supported by several suppliers and their designs adopt commonly used and widely supported standards. The integration of an Open Systems approach into SE governance is necessary to achieve better performance (Hanratty et al., 2002). (OSJT , 2004) argues that an Open Systems approach facilitates the PG by enabling build, upgrade and support of systems more quickly and efficiently through the use of standard commercial products, available from multiple sources.

On the strategy side, the open system approach, improves the PG using a system modular design, well-defined interfaces, design for change and, where possible, the use of widely supported industry standards for key interfaces. For example the U.S. DoD, until about 1990, managed military projects of developing weapons systems with their own unique and closed infrastructures. As a consequence, upgrades or modifications were both problematic and expensive. The reduced budgets and increased dominance of commercial technology made this approach obsolete. An Open Systems Approach can substantially facilitate this leveraging. So the DoD transformed the governance of its own projects, including the use of widely accepted, standard products from multiple suppliers, dividing the project in modules (Hanratty et al., 2002). A governance based on Open Systems Approach produces several benefits, including: risk mitigation of single source of supply (Kowalski et al., 1998); facilitating modular contracting (DoD, 2002); improved level of control over the interfaces used in system development, and the associated processes (DoD, 2001); adapting to evolving requirements and threats integration (OSJT , 2004).

3.1.3 Multidisciplinary Approach

Multidisciplinary Approach is the approach that combines all the appropriate disciplines to identify project solutions in complex environments. SE is based on the Multidisciplinary Approach to ensure customer satisfaction throughout the whole system life cycle (Bahill & Dean, 2009). Customers ask for a project to get a physical infrastructure that will be operated for several years (e.g. a power plant) or to achieve a new configuration for its operation (e.g. the optimisation of a hospital), to develop a new class of products (e.g. R&D for tablets) etc. A multidisciplinary approach enlarges the view from “project success” to its whole system life cycle. The diversity of the elements in a complex system involves a large numbers of different engineering disciplines. For example a nuclear power plant needs a large number of diverse components requiring the combination of several different disciplines, such as mechanical, civil, safety, electrical, electronic, neutronics and software. Moreover its construction requires skill in project management, legal knowledge and the capability to maintain the support of politicians and the public. Each element is part of a system and cannot be designed independently from the other system elements. SE governance guides and coordinates the design, construction, assembly and testing of each individual element to assure that the interactions and interfaces between system elements are compatible. It also ensures that the operations in the construction phase proceed as smoothly as possible (Kossiakoff et al., 2011). The Multidisciplinary Approach and its principles enable the successful management of complex systems when individual elements are designed, tested, and supplied by different organizations in different phases of the project life cycle and operation (INCOSE, 2006) (Kossiakoff & Sweet, 2003).

According to Multidisciplinary Approach principles, SE governance should encompass not only traditional engineering disciplines and their technical and management domains (Ferris, 2008), but also social, political/legal and human factors domains, and include disciplines such as operational research, architectures, modeling, simulation, and more (Kossiakoff et al., 2011).

These softer dimensions require attention to understand their influence in system development. SE, focusing on the system as a whole, looks at the system also from the outside, analysing its interactions with other systems and the environment which can significantly constrains the system development. The objective is that each system fits perfectly with its interfaces. The first step of SE is to understand the environment, process, and policies of a systems problem. The understanding of the environment problems allow the generation of options addressing such problems.

For example, for the realization of a nuclear power plant, SE addresses the key stakeholder needs and the related aspects, including: social acceptability, impact of the procurement of local content, political support, the relationship with the safety authority. The story of nuclear power is marked by expensive failures, not because the technology was faulty, but because managers focused only on technical / constructability issues, forgetting about the (complex) project environment in which the plant was delivered. For instance in Italy and Austria nuclear power projects failed because the population voted against them in a referendum, after the completion of the plants themselves. SE ensures that the system is designed to be compliant with the “soft constraints” of each complex project environment. In conclusion the Multidisciplinary Approach can transform the governance of projects developed in complex environments by paying specific attention to interactions among different system elements, stakeholders and the leading organizations involved.

3.1.4 Top down and bottom up approach (Vee model)

Top down and bottom up approach is a SE methodology to ensure that the system meets the needs and expectations of stakeholders.

Top down approach is for systems design and bottom up approach for system integration (ANSI/EIA 632, 1999). The so called "Vee model" (Forsberg et al., 2005) represents a clear illustration of this idea (Figure 4). The left leg of the "Vee" represents the top down approach: the definition of system and decomposition of it in subsystems, flowing downwards from requirements to design. The right leg of the "Vee" represents the bottom up approach: the iterative process of integration and verification from system components until the system level, validating at sub-levels and customer requirements.

PLESE INSERT Figure 4 HERE

Figure 4 Architecture Vee Model adapted from (Forsberg & Mooz, 1995)

3.2 SE Techniques and Tools

SE is provided with an appropriate combination of techniques and tools (Sage & Armstrong, 2000). The literature analysis lists a large number of tools that can support SE, e.g.: quality functional deployment; test engineering management plan; failure modes and effects analysis etc. This section focuses on SE techniques and tools that can transform the governance of projects delivered in complex environments. Section 3.2.7 compares the PM tools with SE tools.

3.2.1 Integrated Product Team (IPT)

IPT is SE management technique to guarantee the integration of different disciplines viewpoints during the entire system lifecycle (Pyster et al., 2012). "Organizing, using Integrated Process and Product Development Teams" (INCOSE, 2000) is a governance technique that simultaneously integrates all essential activities for system development. Based on a systems approach, it allows the organization to consider all elements of the product life cycle from the concept definition to maintainability in the field. Integrated Process and Product Development uses multidisciplinary teams called IPT (Roe, 1996).

The IPT include all the stakeholders influencing the project success, including customers, end-users, suppliers, subcontractors (DoD, 1998) creating a network of links from the very beginning (Murphy & Heberling, 1996). Each building block (a collection of interrelated work packages) is assigned to an IPT manager, who must have authority and responsibility. The roles of various IPTs and IPT members evolve over the project life cycle (INCOSE, 2000).

The governance based on IPT provides several benefits, including:

- production of a design solution that satisfies customer requirements (INCOSE, 2000);
- integration of business, technical and economic aspects (DoD, 2001) (Kossiakoff et al., 2011) (Ragatz et al., 1997);
- fewer future changes in process planning, and so fewer costly redesign (Dowlatshahi, 1992);
- assessment of the full range of risks that need to be addressed (Pyster et al., 2012);
- maximization of the contributions of each participant and flexibility to obtain the advantages of both the functional and project organization, minimizing the disadvantages of each (Murphy & Heberling, 1996).

3.2.2 System Integration Process

System Integration Process is the process to ensure that all the elements of the system work together to realize the system goals (DoD, 1990). The goal of the System Integration Process is to establish and manage internal and external system interfaces of various kinds including: physical, functional and logical. It ensures that subsystems are integrated into the system and that the system is fully integrated into the larger program (INCOSE, 2000). Governances based on System Integration Process enable the translation of needs of a customer into technical performance specifications, ensuring that system requirements are met (DoD, 1990).

This integrated governance can benefit from a SE systems approach. In the effort to create an effective interface between teams and ensure the proper flow of information, a systematic approach helps to guarantee the inclusion of important considerations. Systematic approaches introduce rigor and structure to the decision-making process. Systematic planning and forethought regarding IPT interfaces can facilitate effective project execution.

Integration must occur both within IPTs and between IPTs. Hence, SE based governance guarantees internal and external integration of IPTs. Knowledge of tasks and their duration is essential to the creation of the Statement of Work, Work Breakdown Structure and Integrated Master Schedule. Leveraging the System Integration Process provides results in improved information flow, better coordination, situation visibility, reduced rework and less frustration for participants (Browning, 1999).

According to (Palmer, 1999), a critical governance issue for the success of a project is the optimal management of subcontractors. System Integration Process uses a set of processes and procedures that relate directly to the activities of subcontractors to assure that their activities performed correctly.

Other aspects that SE focuses on include:

- Review process to keep track of the progress in the resolution of risk items.
- Embedding an audit trail.
- Writing unambiguous instructions as part of the subcontracts and explaining the metrics that enable the assessment of both technical and on-time performance.

The later advantage is accomplished with the approaches and tools aimed to reduce the complexity and uncertainty and increment the flexibility as discussed in sections 3.2.3, 3.2.6. SE promotes, with the application of the System integration process and levering on techniques such as the Vee model and IPT, a modular approach. Modularity is a strategic approach that enables: (1) a rationalised introduction of new technology; (2) a structured approach to dealing with complexity; (3) responsive manufacturing through flexibility/agility (Marshall & Leaney, 1999). According to (Pahsa, 2012), the technical team plays a key role in managing subcontracts. It is involved in activities related to contracting for much of the time. It develops the SE Management Plan (see 3.2.5) according to the acquisition strategy.

3.2.3 Modeling and Simulation

Modeling is a key tool of SE supporting the decision making process. There is an increasing adoption of computer-based tools in place of physical models as mock-ups and even prototypes (DoD, 2001), mainly because virtual models are easily and quickly drawn, shared and updated (Kossiakoff et al., 2011). Models and simulations (1) enable more depth and a more complete analysis of system requirements early in design (2) improve communication because data can be disseminated quickly to several individuals concurrently and design changes can be incorporated and distributed promptly. This is a key aspect in the early phases of a project when the governance is focused on the "Front End Engineering Design" development. The model needs to provide a relatively simple and easily understandable system architecture, useful as a point of reference for discussing the process of developing a new system (Anu, 1997).

Models must be integrated with textual description to fully describe a system: the state of the art of SE is to apply both text and models for the problem description with precision and without wasting SE effort. A good model ensures that at the end of the process all necessary information is available and correct (Oliver et al., 1997).

Systems Modeling Language (SysML) is a standard modeling language for SE application developed to unify the different modeling languages currently used by systems engineers. This improves communication among the involved stakeholders (OMG, 2010). (Willard, 2007) identifies the greatest benefit of SysML to system engineers as the provision of a standard and comprehensive paradigm for system specifications. Diagrams, models, etc. reduce the likelihood of miscommunication, fostering the adoption of standard SysML. The subsequent simulations support the assessment of the dynamic behaviour of a system and its components. Simulation is particularly important for the design of multidisciplinary systems. In these systems the components of different disciplines are closely linked to achieve optimal system performance (Sinha et al., 2001).

3.2.4 Trade-off analysis

The trade-off analysis, or trade study, is an analytical evaluation of alternatives against performance, design-to-cost objectives, and life cycle quality factors (Kossiakoff et al., 2011). It supports decisions throughout SE process solving conflicts and satisfying stakeholder needs, requirements, and constraints (Locatelli & Mancini, 2012b). The trade-offs management is one of the main governance's tasks for projects delivered in complex environments. The goals are (1) to achieve a balanced requirements baseline, (2) to select the functional architecture that is able to meet system requirements and (3) to select the best solution among the candidate designs. (DoD, 2001) highlights that trade study is relevant in other phases as well. In early phase it is useful to examine alternative system-level concepts and scenarios, helping to establish the system configuration. During later phases it is useful to examine lower-level system elements to assist the selection for component part designs.

The trade-off analysis with SE perspective has therefore a wider view than its equivalent in the PM *"The Versatile Artist paradigm aims at maximizing benefits through balancing the diverse set of requirements arising from a number of different stakeholders and their particular needs and desires. Balance is achieved either by tailoring existing project management methodologies or by developing new ones to balance these diverse requirements"*. (Müller, 2009)

Several methods can support the trade-off analysis, the most common are the Quality function deployment (Chan & Wu, 2002)) and the Analytic Hierarchy Process - Analytic Network Process (Saaty, 2004). A good trade study requires the participation of the integrated team; otherwise, the solution reached may be based on unwarranted assumptions or may reflect the omission of important data. For example, the trade studies supported the selection of the International Space Station architecture. The development of the architecture and configuration of the International Space Station modules and crew compartment were based on a very comprehensive set of requirements and analyses. The models assessed many different habitat architectures and selected the final one as a compromise of launch vehicle capabilities, system requirements, past experience, human factors and political consideration (Kitmacher, 2002).

3.2.5 SE Management Plan

The SE Management Plan is the tool that provides to all stakeholders the planned technical effort to accomplish the project.

For instance, considering a NASA project, the Purpose of the SE management plan is *"intended to document the activities to be performed by the NASA Goddard Space Flight Center's System Engineering Office in support of the Laser Interferometer Space Antenna Project's mission formulation. The System Engineering Office will update the System Engineering Management Plan near the end of the Formulation Phase in preparation for the Implementation Phase"* (NASA, 2002).

A critical success factor for effective governance is the plans generation and communication. A best practice to do this is through the SE Management Plan (Sage & Armstrong, 2000).

The SE Management Plan focuses on interface activities with the contractors, including technical team involvement with and monitoring of contracted work. The SE Management Plan (INCOSE, 2000) is the top-level plan for managing the SE effort; and SE is primarily responsible for its creation (Kossiakoff & Sweet, 2003). These activities are important for a subcontractor to fully understand its scope of the work. It defines how (1) the program is organized, structured, and conducted to accomplish SE activities and (2) the SE process is controlled to provide a product that satisfies customer requirements.

Already the first SE standard (DOD, 1969) recognizes the importance of this tool. This first standard requires contractors to implement a SE Management Plan (following the guidelines from the project manager) as part of the concept definition effort. According to (DoD, 2011), the SE Management Plan is a key tool to assess the SE application by several suppliers. The document provides, as an example, contractor's information about which standards, capability models and toolsets are applicable to the programme.

Through the preparation and dissemination of the SE Management Plan the interfaces between participants are defined and controlled. In particular, with the support of the "interface control document", all of the key participants became aware of the responsibilities toward each other, how they interface within each other and also the procedures that must be followed in carrying out the SE tasks. The SE Management Plan is prepared early in the formulation phase and updated throughout the project life cycle (NASA, 2007). (IEEE, 2005) provides a format to help an enterprise to prepare a SE Management Plan. This model must be tailored on the base of program, agency, or company standards.

3.2.6 Requirements Management Tools

Requirements Management is the SE process to capture, analyse and track system requirements (Cant et al., 2006). A critical activity in Requirements Management is to maintain traceability i.e. the *"ability to describe and follow the life of a requirement, in both a forwards and backwards direction"* (Gotel & Finkelstein, 1994). The tool of Requirements Management provides a rigorous "version control" of documents; establishes relationships between document elements and trace relationships between requirements, design, realization and tests (Finkelstein & Emmerich, 2000). Linking requirements to other requirements helps to ensure that nothing is overlooked; reveals which are the other system elements come affected and tracks the status of each requirement during project development.

(Hoffman et al., 2004) identify a number of requirements for this tool applied systems that are complex, highly modularized and organized in product families; the most relevant is the possibility for many users to work on the same data at the same time. The networkability of these tools allows the connection of dispersed IPT and enables program managers and systems engineers to better manage the project (Rundlet & Miller, 1994). This is a key aspect since program managers are responsible for managing related projects in a coordinated way to obtain benefits and control not available from managing them individually. Program managers interact with each project manager to provide support and guidance on individual projects. (PMI, 2008)

3.2.7 SE tools vs. PM tools

SE encompasses several tools and techniques, the ones discussed in the previous paragraphs have been selected because they are appropriate to transform the governance of projects delivered in complex environments. Even if some of the aforementioned tools are used in PM (e.g. the PMBOK (PMI, 2008)) the SE approach to them is radically different. Key conceptual differences between SE and PM tools are due to their different focus, namely system versus project. In other words while the PM applies those tools to the Project the SE enlarges the view to the System and its whole life cycle. This holistic approach radically changes the point of view and the result of the analysis. Table 2 exhibits the main differences between tools applied with the SE or PM perspective.

PLEASE INSERT Table 2 HERE

Table 2 Differences between SE and PM tools

4 Discussion

The SE Approaches and Tools discussed in section 3 and summarised in Figure 3 are the main SE elements that can transform and improve the PG in complex projects environments. Figure 5, grounded on the literature presented in the previous sections, incorporates the main elements of SE and highlights how these elements interact each other. Their application and their interrelationship positively impact on the governance of projects delivered in complex environments.

PLACE Figure 5 HERE

Figure 5 Systems Engineering and Project Governance

The main SE elements are: System Thinking; Open System Approach; Multidisciplinary Approach; Integrated Product Teams; Systems Integration; Modeling and Simulation; Trade Off Analysis; Requirements Management Tools. The types of interactions among these elements fall into two categories: "A enables B" – the application of A allows the correct application of B, namely A is a precondition for the application of B; "A improves B" – the application of A improves the benefits resulting from the application of B. Each interaction is discussed in Table 3.

PLEASE INSERT Table 3 HERE.

Table 3 Definitions of interrelationship among SE elements

SE tools and practices foster and enable the managers involved in the PG to deal with uncertainty and complexity by introducing flexibility and a higher reliability of project planning and control. For example, flexibility is ensured by flexible plans that can be adjusted during project execution; these plans are based on *minimum critical specification* which are generic metrics focused on the scope of the project. Flexibility is also guaranteed by PG's activities related to managing relationships, inputs and outputs across system boundaries. The SE governance is based on mutual adaptation between plans and processes of different actors. ***System Thinking*** enables the consideration and linking of different disciplines (with the relative stakeholders) needed to solve complex problems. This approach requires problem solving to be carried out on a ***multidisciplinary*** basis. Each subsystem is part of a system and cannot be engineered without reference to other system elements. SE guides and coordinates the design of each individual element to ensure that the interactions and interfaces between system elements are fully understood and compatible. This function is one of the more important when individual elements are designed, tested, and supplied by different organizations. The ***multidisciplinary approach*** is expressed by the adoption of one of the core elements of "SE governance": the ***IPTs***, which allow a better governance of all elements of the system life cycle from the concept definition through the design, integration, operations even the decommissioning.

IPTs share a large amount of information. If the division of the system into subsystems is properly done, they can work independently each other, with only occasional feedback to other parts of systems. In particular ***open approach*** & ***modular design***, minimize the interactions among ***IPTs***, improve the interface control facilitating the governance in complex projects environments. The use of IPT from the early project phases enables improved governance by adopting a modular design. IPTs manage the different disciplines to develop the subsystems; but it is the **SE integration process** that enables the governance of several ***IPTs***. The governance is also improved by the system approach, which guarantees the inclusion of important considerations on the right information flow and interfaces. *The integration* process includes the development of an Integrated Master Plan, which provides improved planning and control phases.

Modeling, simulation, and ***trade-off analysis*** are the basic SE tools for decisions support. A good ***trade study*** requires the participation of the ***IPTs,*** otherwise the solution reached may be based on unwarranted assumptions or may reflect the omission of important data. Systems approach provides a cost-effective solution to the customer's problems. ***Modeling*** is the principal means of coping with project complexity. It is based on modeling language standard (SysML); this allows an open approach facilitating the communication among the involved organizations and therefore improving the PG. ***Requirement management*** tools of SE also improve the governance of subcontractors. The networkability of these tools ensures improved sharing of requirements and information with all team members, even if they are geographically dispersed and provides program managers and systems engineers with improved capability in managing the enormous complexity of the project. The application of SE methodology, integrated to PM, in the early stages of the project increases the likelihood of project success. The perfect integration of PM and SE enables improved project estimation effort, complete and correct requirements and establishment of proper agreements with subcontractors.

The program manager is assigned to generate the "request for proposal" while the systems engineer is not officially assigned. It is essential that the technical concepts and the resulting design and interfaces are feasible. The request for proposal includes the statement of work therefore the systems engineer ensures that the scope of work in the statement of work includes all the products and services needed to complete the effort; based on a credible concept of operations and using the possible legacy components. Systems Engineers also examine the availability of "commercial off-the-shelf components" and determines the technology readiness levels for the most important subsystems. The contribution of SE is also important in the improvement of project estimation efforts by ensuring the understanding of the overall system life cycle, the identification of dependencies on other systems and organizations and the identification and planning of resources and key skills.

5 Conclusions and Research agenda

SE is a managerial and technical methodology developed in the last 60 years to improve the governance (and hence the performance) of projects designed and delivered in complex environments. SE achieves these results, transforming the governance from the project and pure "project management" to a more holistic system view of "system management".

The literature review reveals that despite PG being one of the key factors influencing project performance, its optimal form has not been identified yet. Nevertheless SE has emerged as an important technique to transform the governance in complex project environments. SE transforms and improves the PG with several tools and techniques centred on the Systems Thinking approach and the Integrated Product Team technique. Systems Thinking takes into account the environment, and its interactions, in which the project is accomplished. The Integrated Product Team, involving the key stakeholders influencing the project success, enables the definition of a complete and accurate plan with a multidisciplinary and systemic approach. The communication among the involved organizations is supported by requirements management tools. Systems Engineering Management Plan supports the best definition of roles, responsibilities, requirements, interfaces and objectives. The strategic tools that support the Integrated Product Team governance are Modeling, Simulation and Trade off Analysis, which guarantee the delivery of the project with a focus on the benefits over the subsequent life-cycles.

The SE state-of-the-art described in this paper paves the way to test a series of propositions that able to drive the research agenda.

PROPOSITION 1 – The successful application of SE to transform the PG is proportional to the company's maturity in Portfolio Management, Program Management, and Project Management.

RESEARCH ACTIVITY 1- The literature suggests that one of the preconditions to successfully apply the SE principles is a mature managerial culture. However there are not strong and holistic empirical researches testing this hypothesis. By using standards as the" Organizational Project

Management Maturity Model (OPM3)" is possible to assess the companies maturity, therefore the correlation can be tested looking at the result achieved by applying the SE principle. The practical and theoretical implications are very relevant because they demonstrate (or not) that SE can be successfully applied only in mature organisations.

PROPOSITION 2 – The successful application of SE to transform the PG depends on the organisation's structure.

RESEARCH ACTIVITY 2 – The literature speculates that the organization's structure is one of the factors that impacts on benefits of SE application; however it doesn't suggest which is the most appropriate. It is essential to compare cases of application and non-application of SE, for different organisational structures. This analysis would (1) empirically test the hypothesis in the literature and (2) indicate which organisation's structure is more suitable for the application of SE.

PROPOSITION 3a – The application of SE fosters the efficient systems reuse.

PROPOSITION 3b – An efficient systems reuse hedges the risk in delivering projects in complex environments and can cut costs.

RESEARCH ACTIVITY 3 – There is a growing demand for systems with greater performance and wider compatibility, shorter development cycles and lower cost. On the other hand the increasing complexity of systems can lead to longer schedules and higher costs. To face these issues, previously developed systems are frequently reused in modified form in the new system. For example, DoD facing the challenges in defense systems development uses commercial off-the-shelf components wherever practicable. However, integrating different elements together into a developing system can increase the risks instead of reducing them. Focusing on the integration process, a future research stream must investigate how it is possible to leverage the SE for a more efficient systems reuse.

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