Towards systems-of-systems structural resilience assessment

Ilyas Ed-Daoui

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Towards Systems-of-Systems Structural Resilience Assessment

Présentée et soutenue par
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To my parents.

Abstract

Nowadays, we expect of SoS (systems-of-systems) more than just to be functional, but also to be reliable, to preserve their performance, to complete the required functions and most importantly to anticipate potential defects. The relationship with resilience is among the numerous perspectives tackling reliability in the context of SoS. It is about the consequences in case of disturbances and associated uncertainties. Resilience is defined as the ability of systems to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time, composite costs and risks. In this thesis, two complementary approaches are proposed in an attempt to analyze SoS structural resilience. First is related to extensibility which is a specific characteristic of SoS as they are in continuous evolvement and change. A major focus is to evaluate SoS structural resilience with regards to its dynamic aspect and through interoperability assessment. On the other hand, a consideration of the SoS structure and inner workflow pathways represents the second approach. This perspective leads to structural resilience assessment through a set of indicators. Both proposed approaches are deterministic and can be used to evaluate the current state of a SoS structure or to anticipate its resilience in future scenarios. Furthermore, a prototype is designed in order to process the structural resilience assessment. Considering spatial objects, it has been used to conduct experiments on real-based industrial infrastructures approached as SoS.

Keywords: Interoperability; Regional resilience; Reliability; Resilience; Risks assessment; Structural analysis; Structural resilience; System-of-systems (SoS); Territorial planning; Urban planning.

Résumé

De nos jours, nous attendons des SdS (systèmes de systèmes) d'être plus que simplement fonctionnels, mais aussi fiables, de préserver leurs performances, de mener les actions requises et, surtout, d'anticiper d'éventuelles défaillances. La résilience fait partie des nombreuses approches d'évaluation de la fiabilité. Elle est directement liée aux conséquences en cas de perturbations et des incertitudes associées. La résilience est définie comme la capacité des systèmes à résister à une perturbation majeure selon des paramètres de dégradation acceptables et à se redresser dans un délai et à des coûts raisonnables. Dans cette thèse, deux approches complémentaires sont proposées pour tenter d'analyser la résilience structurelle des SdS. La première est liée à l'extensibilité qui est une caractéristique des SdS puisqu'ils sont en continuelle évolution. L'un des principaux objectifs est d'évaluer la résilience structurelle en tenant compte de l'aspect dynamique et moyennant une évaluation de l'interopérabilité. D'autre part, un examen de la structure et des flux internes représente la deuxième approche. Cela conduit à une évaluation de la résilience structurelle grâce à un ensemble d'indicateurs. Les deux approches proposées sont déterministes et peuvent être utilisées pour évaluer l'état de la structure d'un SdS ou pour anticiper sa résilience. Un prototype a été développé pour l'évaluation de la résilience structurelle. Dans la considération des territoires, il a servi à l'évaluation des infrastructures industrielles réelles selon une approche SdS.

Mots-clés: Interopérabilité ; Résilience régionale ; Fiabilité ; Résilience ; Analyse des risques ; Analyse structurelle ; Résilience structurelle ; Systèmes de systèmes (SdS) ; Aménagement du territoire ; Aménagement urbain.

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Acronyms

CS	Component Systems
DB	Degree of Barriers
DF	Degree of Functional barriers
DG	Degree of Geographical barriers
DO	Degree of Organizational barriers
DT	Degree of Technical barriers
EI	Exchange Inefficiency
SE	Systems Engineering
SOI	Structural Operability Indiator
SoS	Systems-of-systems
SoSE	Systems-of-systems Engineering
SoSI	Systems-of-systems Interoperability
SRI	Structural Resilience Indiator

Chapter 1

General Introduction

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1.1 General Context

Recently, there is a growing consensus that SoS (systems-of-systems) concept is an effective solution to implement and analyze large, complex, autonomous and heterogeneous CS (Component Systems) performing collectively Abel and Sukkarieh (2006).

The main thrust behind the exploitation of such systems is to obtain higher capabilities and performance than what could be achieved with a classical system view. The SoS concept presents a high-level viewpoint and explains the interactions between each of the independent CS. However, works on SoS concept remains at their embryonic stages Jamshidi (2008b), Abbott (2006), Meilich (2006).

SoS are qualitatively and structurally different from traditional systems and are not just a larger version of the hierarchical structure Abbott (2006). There are numerous properties that distinguish them.

Their complexity arises from the integration of various independent, evolutionary and distributed systems named CS. They are mutually interacting so as to achieve a higher global target that could not be possible to accomplish individually. This creates one of the main challenges arising from this complexity: the uncertainty of behavior.

This uncertainty results from the absence of fixed specifications, in addition to the coalition of new CS and legacy CS. The integration of widespread CS that interact to achieve SoS target(s) leads to some expected or unexpected emergent behaviors. Moreover, even if the properties of each CS are given and well defined, engineering the whole SoS and predicting its functional and non-functional properties remain challenging tasks.

SoS has received extensive attention in the last years and there has been an increasing number of international conferences, workshops and journals interested in this topic, such as the International Conference on Systems-of-Systems Engineering and the International Workshop on Software Engineering for Systems-of-Systems, International Journal of System of Systems Engineering, etc. to name a few.

The professional community joined efforts to propose new solutions that enable accurate engineering and development of such systems. Moreover, the bibliometric studies in You et al. (2014) and Axelsson (2015) show an increasing number of research publications over time, showing the growing awareness of the importance of SoS engineering.

With the increasing complexity and multi-dimensional structures of the CS, in addition to the growing levels of uncertainties and risks, further development is needed

in some aspects such as risks management, structural analysis, monitoring, resilience quantification and their influence on SoS reliability.

SoS need to be reliable, to preserve the same performance, to complete the required functions and most importantly to be capable of anticipating as many defects as possible. The relationship with resilience is among the numerous approaches to tackle reliability in the context of SoS. Resilience is defined as the ability of systems to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time, composite costs and risks.

Accordingly, assessing reliability and resilience of a synergy of heterogeneous CS has become the focus of various applications, such as: military, aerospace, space, manufacturing, environmental systems, disaster management, critical infrastructures, etc. Jamshidi (2008b), Crossley (2004), Lopez (2006), Wojcik and Hoffman (2006).

1.2 Project Context

The present work is effectuated as part of the European project XTerM (systèmes compleXes, intelligence Territoriale et Mobilité). XTerM is co-financed by the European Union through the European Regional Development Fund (ERDF) and the Normandy Region. The operation that began on October 1st, 2015 will be conducted until September 30th, 2019.

Bringing together a consortium made up of 14 research organizations from 8 institutions (Le Havre Normandy University, Rouen Normandy University, INSA Rouen Normandy, Caen Normandy University, IDIT, NEOMA Business School, ESIGELEC, CESI), this multidisciplinary research project aims to advance knowledge and to propose decision support tools for the management of territories.

XTerM focuses on the development of tools for the "smart" management of territories. Actually, "territorial intelligence" is an arising concept that aims to improve the understanding of territories and inner interactions management.

Territorial development invites researchers and practitioners to better take into account the complexity of territorial systems. These systems are based on networks of interactions that are different in nature and scale (individuals and organizations levels). New technologies, new communication devices, globalized economy and sustainability issues only increase the level of complexity of these territorial systems.

In order to be able to understand this complexity, three fields of analysis are proposed to bridge the gap between modeling and territorial governance:

- The epistemology of the complexity in systems which analyzes the notions and concepts;
- The enrichment of systems knowledge that characterizes territories from a complexity standpoint;
- The development of models and simulations formalizing the complex networks of territories, such as road networks, energy networks, social networks, logistics networks, etc.

Viewed from this perspective, the main focus of the project lies on the following axes:

Complex networks (Réseaux complexes). In this topic, the aim is to study the different forms and stochastic models, that characterize the complexity of these networks. The main focus lies on the impact of network topologies on the dynamics of the systems. Statistical methods to study the dynamics of complex stochastic systems that operate in the uncertain environment are also developed.

Encouraged action spaces (Espaces d'actions encouragées). The interest lies on the mobility of an individual and an aggregate of individuals. This also includes the interactions with their environment through the study of emergence processes and self-organization, that underlie their dynamics. This thematic focuses on showing the temporary nature of these interactions and in particular the non-linear aspect of their dynamics; that is to say that the mobility of an individual and an aggregate of individuals has a relative sensitivity to the initial conditions that can lead to a macroscopic reorganization of the interactions with the environment. The intent is to know how the design of encouraged actions spaces can disrupt, destabilize, or offer possibilities of action and lead to certain flexibility or contrary to a form of resistance of the behavior in the face of the changes related to the environment.

Movement and complexity (Déplacements et complexité). The thematic on movement and complexity is part of a scientific approach, that questions the ability of soft and massive data from connected objects to constitute a new resource for understanding urban rhythms and mobility in territories. The results of the application to connected objects show that users do not invest in a ubiquitous way the urban space and associate some forms of hotspots with sporadic frequentation. The observation of the results generally reveals a great variability and the complexity of users' movements in urban spaces and territories. This thematic interest is on the ability to present the interest and the limits of the soft data to renew the approaches of mobility. It also focuses on the movements of connected objects that reflect both forms of permanence and uncertainty in the places frequented and the emergence of

ephemeral concentrations, depending on several parameters including transportation modes.

Territories and sustainable mobility (Territoires et mobilité durables). To improve the sustainability of mobility in territories, public decision-makers need tools to know the occupation and use of this territory (characteristics of populations, routes and modes of travel, daily journeys, infrastructures, etc.) and to understand the impact of the devices at their disposal (impact on travel modes, journeys, emissions, etc.). A number of communities already have such foresight tools, and others have an interest in being able to do so in the near future. It will be possible to discuss the existing avenues and the means that are implemented to carry out this model (data collection via new surveys, use of big data, development of new models, coupling of models, renewal of existing approaches).

Economic and industrial infrastructures (Territoires économiques et industriels). This is the axis that embraces this thesis. It includes the analysis of the stakes, the industrial and logistic sectors transformations, that makes it possible to observe important evolutions related to systems flexibility. This is also reflected in the digitization of the processes and transformations of the organizations and the management methods of these systems, from the production to the logistics. The developments are based on information and communication technologies (Internet of Things, connected machines, big data, supervision software, artificial intelligence, etc.), associated with the rise of robotics (mobile robotics, collaborative robotics, etc.) and modeling, simulation and optimization of complex systems.

1.3 Research Problem Statement

One of the founding principles of reliability is the need to take a systems approach to understand how an organization or a composition of components succeeds and sometimes fails in managing increasingly complex systems, especially, in highly pressured contexts. A systems approach to tackle reliability in complex systems requires a shift in how to study, model and measure operational processes Reason (2016).

In reliability literature, resilience represents the ability of a system to "adjust its functioning prior to, during, or following changes and disturbances, so that it can continue to perform as required after a disruption or a major mishap, and in the presence of continuous stresses" Hollnagel et al. (2006), Cedergren et al. (2018), Patriarca et al. (2018).

While in the context of SoS, resilience remains difficult to interpret. However, it

is generally known as the capacity of a system to resist an unpredictable event or a risk and recover. It concerns consequences in case of risks and inherent uncertainties.

Comprehending resilience can be useful and practical to tackle SoS reliability and safety along with survivability and trustworthiness. There is a common belief that reliability and resilience concepts are strongly related, however, studies to endorse this belief are still lacking. This thesis aims to emphasize the mutual correspondence between the two concepts.

In literature, there is also perceptible shortness of works dedicated to fully address the resilience of SoS through structural analysis as well as the assessment and evaluation of SoS structure and operability level.

Approaches to quantify the impacts of CS on the global system's viability and the impact of the process within the SoS on each one of the CS also lack the literature.

Therefore, this helps to be cognizant of the rate of the system's survivability after each CS failure, integration, segregation, etc. which also helps to locate impactful (and vulnerable) CS and predict their impacts (and their susceptibility) on (to) the SoS structure and the overall working process.

1.4 Contribution Outline

After reviewing SoSE (SoS Engineering) related literature, the strength of the correlation between resilience and reliability is leveraged. The aim is to emphasize the mutual correspondence between the two concepts. Resilience assessment implies the implicit evaluation of reliability.

Deterministic approaches are proposed to assess SoS resilience through structural analysis. Furthermore, the proposed structural analysis approaches are an attempt to bridge the gap between SoS, resilience and reliability.

The first proposition is related to extensibility which is a specific characteristic of SoS as they are in continuous evolvement and change. A major focus is to evaluate SoS structural resilience with regards to its dynamic aspect and through interoperability assessment.

The second contribution represents a consideration of the SoS structure and inner workflow pathways. This perspective leads to structural resilience assessment through a sequence of calculations.

In an attempt to combine resilience with the spatial object's structure in addi-

tion to the embraced workflow pathways, a prototype is designed. The combination of the resilience concept with the spatial object aims to assess and measure the regional development. It also helps to anticipate and evaluate the impacts of threats targeting an area to elaborate plans and take actions to mitigate their impacts. This combination also takes into account the region's inner behaviors, culture and policy contribution

1.5 Published Works

Book

- Ilyas Ed-daoui, Tomader Mazri, Nabil Hmina, "*Towards Reliable IMS-based Networks: Principles, Analysis and Application*", LAP LAMBERT Academic Publishing, Germany,ISBN: 978-3-330-06208-5, March 2017.

International peer-reviewed journals papers

- Ilyas Ed-daoui, Abdelkhalak El Hami, Mhamed Itmi, Nabil Hmina, Tomader Mazri, "*Resilience assessment as a foundation for systems-of-systems safety evaluation: Application to an economic infrastructure*", Safety Science, Elsevier BV, Netherlands, DOI : 10.1016/j.ssci.2019.02.030, Vol. 115, pp. 446-456, 2019.
- Ilyas Ed-daoui, Aicha Koulou, Norelislam El Hami, Abdelkhalak El Hami, Mhamed Itmi, Nabil Hmina, "*An Approach to Systems-of-systems Structural Analysis throush Interoperability Assessment : Application on Moroccan Case*", International Journal of Engineering Research in Africa, Trans Tech Publications, Switzerland, DOI : 10.4028/www.scientific.net/JERA.41.175, Vol. 41, pp. 175-189, 2019.
- Ilyas Ed-daoui, Mhamed Itmi, Abdelkhalak El Hami, Nabil Hmina, Tomader Mazri, "*A Study of an Adaptive Approach for Systems-of-systems Integration*", International Journal of System of Systems Engineering, Inderscience Publishers, UK, DOI: 10.1504/IJSSE.2019.097895, Vol. 9, No. 1, pp. 1-27, 2019.
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- Ilyas Ed-daoui, Mhamed Itmi, Abdelkhalak El Hami, Nabil Hmina, Tomader Mazri, "*Systems-of-systems and regional resilience assessment: A proposition of a structural indicator*", To be submitted.

1.6 Thesis Organization

Chapter I - General Introduction

This chapter represents the general introduction to this thesis. It introduces the general context of the conducted study. It also details the European project embracing this thesis. Research problems and the main contributions to answer and overcome these challenges are stated. Published works are also listed.

Chapter II - Literature Review

Even if the purpose of this thesis is not a complete systemic literature review, an evaluation of some of the existing and pertinent approaches that have been published is conducted. The idea is to gain insight into the current status of SoS resilience evaluation, quantification and assessment research.

The extraction of the publications was done in a structured way by using appropriate keywords related to systems-of-systems, systems-of-systems engineering, resilience, reliability, safety, structural analysis, regional resilience, regional competitiveness, regional development, risk assessment, interoperability assessment, etc. Several inclusion and exclusion criteria are used to select relevant studies.

SoS definitions, properties, taxonomy and prominent frameworks and standards in addition to SoS engineering are detailed in this chapter. A chronological overview of some contributions in the SoS/SoSE area is also presented. A description of reliability and resilience in the context of SoS is also done in this chapter.

Chapter III - SoS Structural Operability Assessment

In this chapter, an approach to SoS structural resilience evaluation through interoperability assessment is presented. It is related to the dynamic aspect of SoS. It is also a response to the growing need for the exploitation of such systems and the rapidly increasing cost incurred by loss of operation as a consequence of failures.

In addition, an illustrative classification of interoperability properties is detailed. In this taxonomy, the focus is on some important axes in the analysis and evaluation of the SoS structure.

The proposed approach is based on structural analysis and dedicated to assess the functional interdependencies between systems. This process should be applied, similarly, to every single interdependency based on the global system's structure.

Chapter IV - SoS Resilience Assessment Trough Risk and Structural Analysis

This chapter is an attempt to respond to the concerns related to SoS resilience through structural analysis and risks management. The SoS structure is modeled as a directed graph emphasizing its static aspect. The nodes can represent either the CS or capabilities that need to be acquired. Correspondingly, the links represent the interdependencies between the systems or between the capabilities.

An approach is proposed to anticipate risks, their influences and impacts, which contributes to the quantitative anticipation of SoS resilience. This also implicitly embraces a step towards reliability evaluation and enhancement.

The risks management is based on two important steps: a risks classification which lies on their natures and sources and a risks monitoring which is conceived to evaluate, analyze and supervise risks which represent the catalyzers of destabilizations.

While the structural analysis starts with functional interdependencies assessment. Next, it estimates the dependency of the process continuity on every CS and the influence of each CS on the overall process within the SoS, thanks to a sequence of calculations.

Chapter V - SoS and Structural Analysis as a Basis to Regional Resilience Assessment

This chapter resumes an attempt to answer to the concerns related to regional resilience. A prototype is designed to combine resilience with the spatial object's structure in addition to the embraced workflow pathways. The combination of the resilience concept with the spatial object aims to assess and measure the regional development and evolution.

This combination also takes into account the region's inner behaviors, culture and policy contribution. it helps to anticipate and evaluate the impacts of threats targeting an area to elaborate plans and take actions to mitigate their impacts.

The approach is based on the engineering aspect and aims to assess the structural resilience of economic infrastructures amid a region. It may also be extended to include the ecological and social aspects, as long as they can also be approached as a SoS.

Chapter 2

Literature Review

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2.1 Introduction

SoS and SoS Engineering (SoSE) have attracted the attention of the research community since their applications included numerous modern society solutions.

A large number of challenges related to the different phases of the SoS development cycle were identified by recent works and one of the biggest is related to reliability and resilience assessment. Works in this field are in the embryonic stages of development and lack consistent focus.

To gain insight into the current status of SoS resilience evaluation, quantification and assessment research, a review of the related existing and pertinent approaches that have been published is conducted.

Since the objective of this thesis is to assess the SoS structural resilience, in this chapter, a number of existing approaches and works that jointly or partially address SoS, reliability and resilience are gathered and reviewed. The publications presented and analyzed in this chapter were extracted from several bibliographic databases, mainly: Sciencedirect, IEEE Xplore, ACM digital library, Springer, Wiley online library, etc.

The extraction of the publications has been carried out in a structured way by using appropriate keywords related to the topics of interest, in addition to several inclusion and exclusion criteria in order to select relevant studies.

The related works are collected and evaluated with the main research questions in mind. Still, the main focus of this thesis is not a completely systematic literature review. The remaining part of this chapter is organized as follows:

- A proposition of SoS definitions, properties and taxonomy is given in Section 2.
- Section 3 details SoS engineering and presents chronologically a large overview of some contributions in the SoS/SoSE area.
- A presentation of the three prominent frameworks and standards is given in section 4.
- Section 5 provides some definitions to the reliability and proposes a classification of approaches to tackle it.
- Section 6 describes resilience in the context of SoS
- Section 7 draws conclusions.

2.2 Systems-of-systems (SoS)

2.2.1 SoS Definitions

As SoS have received extensive attention from science communities in the past years, numerous definitions were proposed to sire this concept. Table 2.1 enumerates some of the numerous proposed definitions of SoS.

Therefore, the SoS commonly consented definition that embraces a maximum of properties is the following Ed-daoui et al. (2018a), Ed-daoui et al. (2017a):
"SoS are an evolving synergy of heterogeneous, autonomous, distributed, interdependent, sometimes complex and integrated systems that interact in order to achieve a complex and evolving target that exceeds the sum of the parts."

Despite the fact that the term SoS has been around for quite a while, we still seem to be struggling with the concept. Jamshidi quoted approvingly from the claim in Sage and Cuppan Sage and Cuppan (2001) that there is no universally accepted definition of SoS. Besides, most definitions of SoS are not very helpful and some of them are even harmful Abbott (2006).

Besides, Application areas of SoS are vast indeed. They are software systems like the Internet, cloud computing, health care, and cyber-physical systems all the way to such hardware dominated cases like military, energy, transportation, etc. Tannahill and Jamshidi (2014).

Authors or organizations	**Definitions**	**References**
Department of Defense (USA)	"SoS is a large-scale composite system, which can realize specific function" "SoS are a collection of systems, each capable of independent operation, that interoperate together to achieve additional desired capabilities"	DoD USD (2008)
Kotov Vadim	"SoS are large scale concurrent and distributed systems that are comprised of complex systems"	Kotov (1997)

Jamshidi Mo	"SoS are integrated, independently operating systems working in a cooperative mode to achieve a higher performance." "SoS are large-scale integrated systems which are heterogeneous and independently operable on their own, but are networked together for a common goal"	Jamshidi (2008b)
Maier Mark W.	"SoS as a collection of systems that must have two features: its components must be able to operate independently by the whole system and they do operate independently, being managed at least in part for their own purpose"	Maier (1996)
Varga Pal, Blomstedt Fredrik, Ferreira Luis Lino and al.	"SoS are a set of systems working together to achieve a more complex target or a higher purpose "	Varga et al. (2017)
DeLaurentis Daniel	"A SoS (SoS) consists of multiple, heterogeneous, distributed, occasionally independently operating systems embedded in networks at multiple levels, which evolve over time"	DeLaurentis (2007)
White Brian E	"SoS is a collection of systems, that can achieve the objective which a single system cannot achieve. Every system can operate independently to achieve its own objective. SoS have emergence properties"	White (2016)
Xia Boyuan, Zhao Qingsong, Dou Yajie and al.	"SoS are special systems, they are composed of systems which can run independently and have their own benefits and value. Once the element system is put into the SoS, its independence still exists and the interactions among the systems are frequent."	Xia et al. (2016)

Table 2.1:: Collected SoS concept definitions.

2.2.2 SoS Properties

SoS are qualitatively and structurally different from traditional systems and are not just a larger version of the hierarchical structure Abbott (2006). In addition, they have numerous properties that distinguish them. These properties are classified into two classes: systemic properties and functional properties.

The Systemic Properties

At this level, the attention is directed to the CS forming the SoS and the relationships between them. Accordingly, the idea is to find out how that structure is achieved and we implicitly define that extra-something which differs SoS from a simple collection of parts. The word "*extra-something*" is inspired by Boardman and Sauser (2006).

It is worth noting that the structure is not stable, it is continually changing and evolving in correspondence with the evolvement of the target(s) of the SoS Abbott (2006).

The structure includes the interconnected CS and resources that support the SoS. The CS may be heterogeneous, autonomous, distributed, interdependent, complex and perform in collaborations.

From a systemic perspective, there are a variety of properties and characteristics that distinguishes SoS from systems as traditionally understood. These properties are detailed in the following.

Autonomy

From a technical point of view, there are two notions siring the concept of autonomy. One is called self-directness which refers to the independence of a system from any external intervention to perform correctly. The other is self-sufficiency which refers to the non-reliance of a system on any external intervention to satisfy its need Bradshaw et al. (2004), Bradshaw et al. (2003), Johnson et al. (2014).

Autonomy may be considered as a task for the system itself, as the system exists to perform independently. However, autonomy implies some constraints. It should be noted that the constraints should not be permitted to overwhelm or violate its performance Boardman and Sauser (2006).

It is true that any CS may fail to fulfill its task within the SoS, but autonomy should not be accepted as a reason. The problem might more likely to be due to a lack of efficiency, effectiveness or even compatibility.

Authors of the paper Boardman and Sauser (2006) claim that the notion of autonomy has been neglected in the systems approach which explains why some systems are recognized as such, even when they act as items.

In some cases, the difference between an item and a system becomes difficult to prove, as an item may have relations, perform dependently and form a whole. However, a system is more complex than that, it is a set of items.

Heterogeneity

Heterogeneity is a very complex issue, as SoS should support the diversity of CS natures in addition to their operation on different time scales. This creates a challenge for SoS to perform without being affected by the divergence regarding the nature and operation schedule of its components.

A SoS should be diverse in terms of resources, functionalities and capabilities. Correspondingly, the difference should be made between requirements-driven SoS, which are based on the defined intent, and capabilities-based SoS, that exhibit functions diversity Boardman and Sauser (2006).

In addition, a simple system can produce an aperiodic and complex performance, with sometimes endless varieties of trajectories which should eventually converge to unified patterns. This implies that vigilance is needed when dealing with diversity.

Correspondingly, SoS need to be heterogeneous regarding resources and diversity when it comes to functionalities and capabilities Boardman and Sauser (2006).

Interdependence

In the design of a SoS, interdependencies are considered simultaneously with CS and capabilities. There is a need to create, manage and enhance interdependencies and achieve interoperability, amid legacy CS, capabilities and added CS and capabilities.

Interdependencies are concerned by the ability of CS capabilities to share, exchange and correctly interpret information, material and sometimes even energy, in order to achieve a common goal in a given context respecting rules of interaction Billaud et al. (2015), DeLaurentis (2005). This implies the resolution and management of the CS amid the SoS in addition to their inherent connectivity that does not appear.

Moreover, systems themselves have the responsibility to determine their interdependencies. This is propitious to the systems self-directness autonomy. However, it is mandatory to be directed by the fulfillment of the mission of the SoS.

It should be noted that talking about interdependencies implies talking about interoperability, which represents the ability of at least two systems to understand one another and to mutually share and exploit their functionalities and information despite their heterogeneity. It is needed to assess the heterogeneity of their natures, functionalities and capabilities.

Distribution

CS within the same SoS are not forced to be physically collocated in the same geographic locus and managerially centralized in order to achieve a common purpose. Correspondingly, the geographic extent of SoS is large and nebulous Maier (1996).

Information, tasks and capabilities are distributed amid the SoS according to some rules. And this distribution should not be considered as a limitation. Moreover, there is also managerial decentralization which means that there is no reliance on a system or a set of systems for the management of the SoS.

Extensibility

There is no fixed structure for SoS. The structure may evolve, extend or even shrink at any time Abbott (2006). This distinguishes them from systems as traditionally understood, as it, continually, enables the integration and segregation of CS. However, the changes should not hinder the achievement of the global target in any manner.

Correspondingly, the evolutionary model is not exclusive to the structure. This property also concerns capabilities and targets. In some cases, evolution is related to the environment embracing the SoS itself.

The Functional Properties

Dealing with SoS implies being faced with two verities. The first one is the physical structure which represents the CS. The other is the contribution of this structure, in other words, the purpose behind gathering them and making them work together.

Apart from systemic properties, that focus essentially on the structure, there is another important set of properties, that characterizes SoS, which is called functional properties. At this level, the focus is on the SoS functions in addition to the organization of services and capabilities.

Besides structure, there are also services which stand for defined objectives of a collaboration of some resources amid the SoS structure. The services are the aim of a cooperation, hence they contribute to the progress towards an underlying and a

global intent. The latter is the aim of the SoS which represents the sought solution that all the infrastructure is assembled to achieve.

However, there is a huge constraint in the design of SoS. It is the competitiveness of needs Jamshidi (2008b) which leads to the solutions' tendency to compete. Besides, the viability of a solution cannot be evaluated without consideration of the circumstances that drive the need for it.

We understand that we can never affirm that a SoS is completely finished. It changes and matures constantly according to the environment embracing it, which also evolves Abbott (2006).

SoS should be capable to support new uses, new standards and new technologies of existing features in addition to the integration of new features and the segregation of existing ones.

Therefore, systems with such complex properties do not lend themselves to easy control and are not formless. This represents the main challenge of SoS management.

The Manipulation of Resources to Achieve the Target

SoS implementation starts with the recognition of a need or a combination of needs. Then comes the definition of an objective related to overcoming the defined needs, and after that, a manipulation of resources is performed in order to distribute the defined aim into different services.

The manipulation of resources cannot be performed randomly or without considerations regarding the consistency of CS within the SoS. The distribution of the SoS goal into several services implies the organization of resources in the infrastructure layer so as to achieve each service. One of the most critical challenges in the manipulation of resources is to handle the integration process, as SoS include a set of autonomous CS that were neither conceived to perform together nor designed as parts of a larger system.

Thus, the newly integrating CS should have the ability to communicate with the SoS or a part of it without compatibility issues. Correspondingly, as the integration process, systems' segregation should not cause functional problems.

Another aspect to be considered is that each system within the SoS is likely motivated by a set of needs which may change over time. This introduces some unavoidable complexities, especially in terms of constraints, consequences and emergences.

Emergence

In Johnson (2006) and Damper (2000), authors assume that there is no concise

and generally accepted definition of emergence in the SoS context Jamshidi (2008b).

However, in Brownsword et al. (2006), authors see that they represent a form of behaviors that unbounded systems display and that differ from the collective properties of the CS forming the SoS. These behaviors emerge from the cumulative actions and interactions of the component propagated throughout the SoS and can they have a positive or negative effect.

In the best case, they will provide unanticipated benefits in order to contribute to the achievement of SoS targets. In the worst case, they will hinder the overall performance of the SoS Boardman and Sauser (2006).

2.2.3 SoS Taxonomy

In order to enable knowledge transfer to areas working with systems that exhibit exclusively some SoS characteristics, a classification is suggested. The proposed classification is based on the level of both management centralization and systems' operational freedom.

According to DoD USD (2008) and the Systems Engineering Guide for SoS (SEGS) published in 2008, a SoS can be classified according to the way it is managed in addition to its ability to adapt to changes.

Directed SoS

Directed SoS have well-defined objectives, and they are built to fulfill specific purposes. It may also have a designated manager and resources, etc. They are centrally managed during long-term operations to achieve the targets. However, CS remain autonomous and maintain the ability to perform independently. Example: airports.

As depicted in Figure 2.1, there is a hierarchy of targets amid directed SoS. However, the most crucial ones are SoS targets which stand for the global and final intents of the construction of the SoS. They represent the sought solutions that all the infrastructure is assembled to achieve.

Below SoS' ultimate targets there are a set of objectives that collaborate so as to achieve all the targets of the directed SoS. They form a certain descending hierarchy of objectives. The idea behind this hierarchy is to decompose a complex target into few complex objectives. The same process goes for the objectives that are also decomposed into several tasks.

The decomposition of targets and objectives into smaller, more manageable, directed and clearer ones will end when we get to more or less simple and defined tasks that will be assigned to CS. Therefore, all autonomous and heterogeneous CS will have independent tasks that implicitly contribute to the achievement of the global targets of the SoS.

It is worth noting, that the notions of "target", "sub-target", "ob" and "task" in Figure 2.1 and Figure 2.2 are meant to emphasize the hierarchy and to demonstrate that there are different levels of objectives. Thus, the nominations are only used for explanatory purposes.

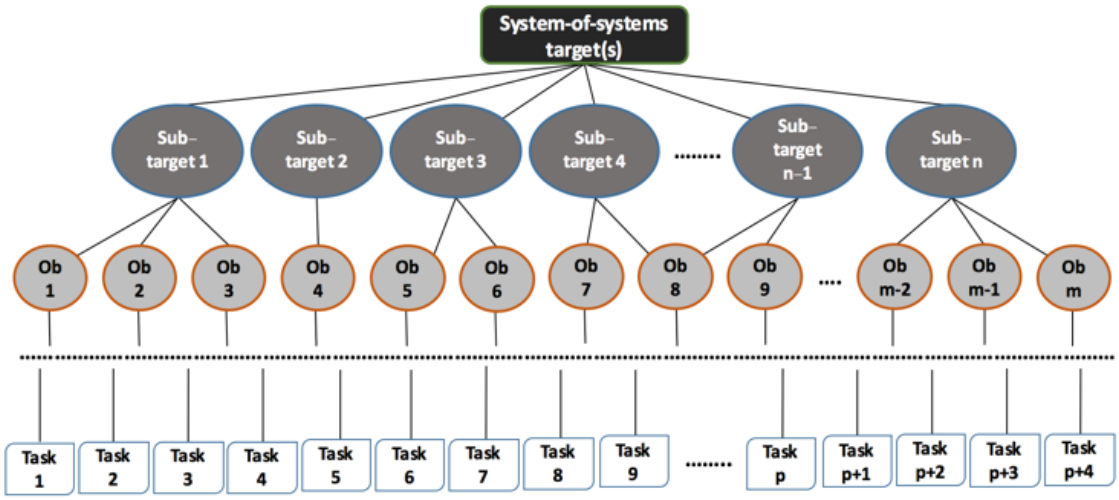

Figure 2.1: Illustration of directed SoS.

Open SoS

In this SoS class, there can be neither a central management authority nor a centrally agreed-upon purpose. However, there are only some targets that CS interact more or less voluntarily to achieve. They can integrate or exit the SoS dynamically based on mission requirements. This class may be more threatened by emergence. Examples: national economy.

In contrast to directed SoS, open SoS have no central management authority and no centrally agreed-upon purpose. CS participate dynamically in the performance of the SoS in order to achieve its decentralized objectives.

Table 2.2 highlights the main differences between open SoS and directed SoS. It focuses on the dissimilarities in management and objectives organization.

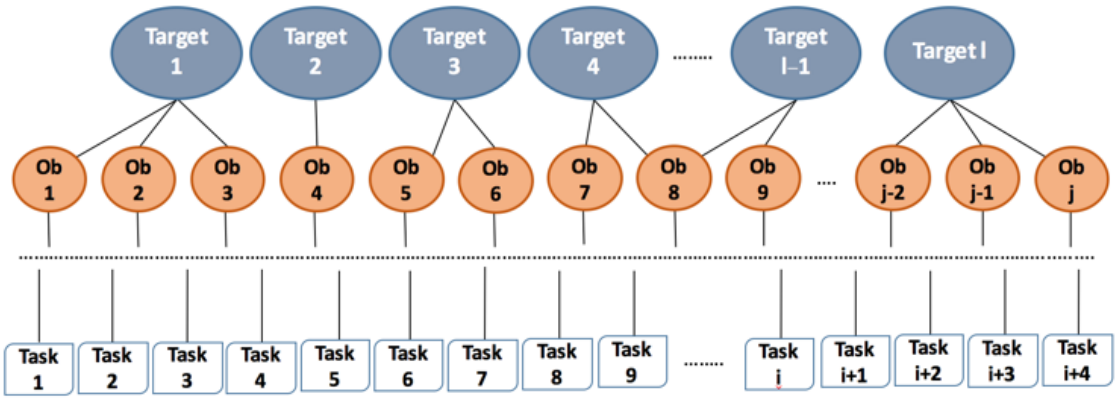

Figure 2.2: Illustration of open SoS.

Open SoS	**Directed SoS**
No central management authority	Centrally managed
No centrally agreed-upon purpose	Well-defined objective(s)
Voluntary interaction in order to achieve some objectives	Built to fulfill a specific purpose
Dynamic integration and segregations based on mission requirements	It may have a designated manager and resources

Table 2.2:: Major divergences between open and directed SoS.

It is worth noting that the form and rigor of the integration process are strictly related to the SoS class. From a managerial standpoint, the integration in a directed SoS may be easier than in an open SoS.

It is important to mention that in order to successfully integrate a CS in a SoS, regardless of its type, the system definitely needs to be in coherence with the interoperability rules of the SoS Madni and Sievers (2014).

In an open SoS, new systems may enter and leave the SoS without knowing the impact on the integrity of the SoS. While in a directed SoS, the CS are inspected, validated and trusted Madni and Sievers (2014).

Figure 2.3 illustrates that if the SoS is oriented to more management and less operational freedom, it approaches directed SoS. On the other hand, if it is oriented to less management and more operational freedom, it approaches open SoS.

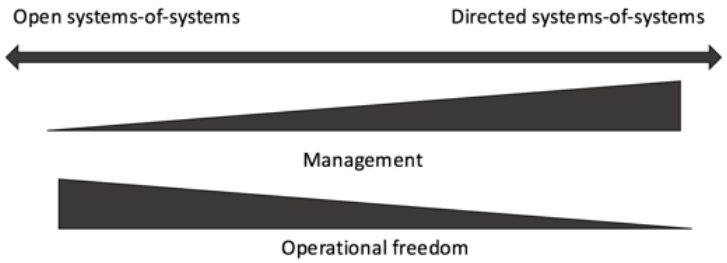

Figure 2.3: Difference between open and directed SoS. Focus on management and operational freedom.

2.3 SoS Engineering (SoSE)

The technological, human and organizational issues are much more different when considering a SoS or a federation of systems. These needs are very significant when considering SoS engineering and management Jamshidi (2008b).

This precipitated the emergence of a new discipline, which is called SoS engineering (SoSE). A discussion of SoSE is included in DoD USD (2008): "SoS engineering deals with planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a system of systems capability greater than the sum of the capabilities of the constituent parts."

Actually, this discipline develops and becomes more mature every year as there is a growing interest in SoSE standardization. This includes more convergence on definitions and fundamental principles Dahmann and Roedler (2016). Hence, this would establish a fructuous basis for more consistent and effective research as well as the application of the theories.

Today there is a huge interest in the engineering of systems containing other CS, where each of the CS serves organizational and human purposes Jamshidi (2008b). However, in the SoS field, there is an unsolved problem practically anywhere one points, and immense attention is needed by engineers and scientists Kumar (2014).

So, the question is: "how could we analyze SoS structure?"

The SE (Systems Engineering) realm has been well established which concerns the engineering of complex systems. However, the area of study in the engineering of SoS needs much attention. Besides, there was a need for an independent field focusing on the engineering of multiple integrated complex systems (i.e. SoS). Today, this discipline is known as SoSE. However, the scientific community is still struggling to understand its principles, practices, and execution Gorod et al. (2008). In order

to distinguish systems engineering and SoSE, a description is given in the table from Keating et al. (2003).

Area	**SE**	**SoSE**
Analysis	Technical dominance	Contextual influence dominance
Approach	Process	Methodology
Boundaries	Fixed	Flexible
Expectation	Solution	Initial response
Focus	Single complex system	Multiple integrated complex systems
Goals	Unitary	Pluralistic
Objective	Optimization	Satisfying
Problem	Defined	Emergent

Table 2.3:: Highlight of the divergences between SE and SoSE.

Although their dissimilarity in fundamental aspects, as depicted in Table 2.3, systems engineering provides an important potential foundation in SoS conceptualization and realization. Here are some points from systems engineering that SoSE should not neglect, as they will only serve to strengthen SoSE development as an evolution of traditional systems engineering, these points are extracted from Kumar thesis Kumar (2014):

- The linkage to systems theory and principles for design, analysis and execution
- Interdisciplinary focus in problem-solving and system development
- Emphasis on disciplined and structured processes to achieve results
- The iterative approach to develop systems to meet expectations for problem resolution

In an attempt to sire the SoSE concept, a definition has been proposed in Keating et al. (2003):

"The design, deployment, operation and transformation of metasystems that must function as an integrated complex system to produce desirable results. These metasystems are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography and conceptual frame".

The chronologically presented works describe some of the contributions in SoS, SoSE and related subjects. Most of these points are collected from Kumar (2014):

- Eisner et al. (1991): described the role of computer tools to develop the SoSE field.
- Maier (1996): provided an important contribution in the field of SoS and proposed a definition, taxonomy and a basic set of architecting principles to assist in SoS design.
- Kotov (1997): presented a communicating structures library (CSL) which is a C++ based library and an object-oriented core environment for the modeling and analysis of SoS in the framework of Communicating Structures. It includes both simulation and analytical (queueing analysis) options as well as GUI for the model construction and visualization tools for analysis of the modeling results.
- Sage and Cuppan (2001): provided detail study on systems; SoS and federation of systems (FoS). In addition, engineering and management of SoS and FoS are described with emphasis on defense systems.
- Keating et al. (2003): described the issues in SoSE with a detailed literature review. Current and future perspectives of SoSE are provided, with implication for design, deployment, operation and transformation of SoS.
- Allison et al. (2004): presented some additional characteristics of SoS that should be included in a more comprehensive and generalized definition and highlighted some issues in SoS characterization. From analysis they concluded that these following characteristics were common across the three fields of biology, sociology and military: evolutionary development, emergent behavior, self-organization, adaptation, complex systems, individual specialization and synergy; but other properties may not be satisfied.
- DeLaurentis and Callaway (2004): explained the SoS perspectives in decision making, and exemplified by the next generation of transportation system.
- DeLaurentis (2005): introduced an emerging class of problems called SoS, present the primary traits of the class, and then described the relevant implications for the aerospace design community.
- Boardman and Sauser (2006): described five characteristics for a SoS namely, autonomy, belonging, connectivity, diversity and emergence. It is explained that both system and SoS consist of parts, relationships and a whole, that is greater than the sum of the parts. However, these terms differ in a fundamental sense, that impacts their structure, behavior and realization, as well as the distinction that comes from the manner in which parts and relationships are gathered together and therefore in the nature of the emergent whole.

- Brownsword et al. (2006): introduced the SoS Navigator (SoS Navigator), the collection and codification of essential practices for building large-scale systems of systems. SoS Navigator provides tools and techniques to characterize organizational, technical, and operational enablers and barriers to success in a system of systems; identify improvement strategies; and pilot and institutionalize these strategies.

- Abbott (2006): described the main differences between SoS and traditional systems.

- Carlock and Lane (2006): provided an overview of the SoS ECE and Enterprise Architecture Management Framework (EAMF), provided an overview of the University of Southern California (USC) Center for Systems and Software Engineering (CSSE) SoSE cost model, attempted to evaluate how well the EAMF captures the unique aspects of SoSE identified in recent SoSE studies and showed how the cost model addresses some of the unique aspects of SoSE identified in both the EAMF and recent SoSE studies.

- Sahin et al. (2007): presented a simulation framework for SoS architectures. The application of extensible markup language (XML) is described to represent data communicated among heterogeneous constituent systems of a SoS.

- West (2007): presented a real-world, industry perspective of the challenges associated with operating a global Live, Virtual, Constructive (LVC) environment.

- Kewley et al. (2008): highlighted how capabilities for information exchange, environmental representation, entity representation, model development, and data collection support the federation development process for SoS.

- González et al. (2008): presented ATLAS, an architectural framework that enables the run- time integration and verification of a system, based on the built-in test paradigm. ATLAS augments components with two specific interfaces to add and remove tests, and to provide adequate testability features to run these tests. SoS (SoS) represent a novel kind of system, for which runtime evolution is a key requirement, as components join and leave during runtime. Current component integration and verification techniques are not enough in such a dynamic environment.

- Simpson and Dagli (2008): analyzed characteristics and attributes of systems and SoS. The following key system attributes and characteristics have been identified as essential components of successful systems: flexibility, adaptability, modular design, open interfaces and contextual awareness as well as local system control over the connection to global SoS resources.

- Gorod et al. (2008): provided a detailed literature review on SoS, and described the management framework for SoSE. A case study is provided to illustrate how the proposed framework could be applied.

- DeLaurentis (2008): described the modeling and analysis of a SoS. Taxonomy is proposed to model road transportation, air transportation and space transportation.

- Valerdi et al. (2008): documented the activity of a workshop on defining a research agenda for Systems of Systems SoS; Architecting, which was held at USC in October 2006. After two days of invited talks on critical success factors for SoS engineering, the authors of this paper convened for one day to brainstorm topics for the purpose of shaping the near-term research agenda of the newly convened USC Center for Systems and Software Engineering (CSSE).

- Jamshidi (2008b): introduced a book dedicated to SoS. It covered a wide variety of SoS topics including principles, architecture, applications, etc.

- Mahulkar et al. (2009): described agent-based modeling for a SoS. The SoS approach is applied for modeling and simulation of a ship environment with wireless and intelligent maintenance technologies.

- Mansouri et al. (2009a): proposed a framework to engineer and manage maritime transportation systems from a SoSE perspective.

- Baldwin and Sauser (2009): described a theoretical model using set theory to define five characteristics of a SoS: autonomy, belonging, connectivity, diversity and emergence. In addition, agent-based modeling and simulation are described for SoS.

- DiMario et al. (2009): described the SoS collaborative formation and formed a case study on autonomous systems.

- Sauser et al. (2010): described an approach to provide an insight of SoS. A foundation is established to understand the behavior of SoS by a deeper analysis of their structures using biological analogies.

- Ender et al. (2010): proposed a modeling and simulation framework that supports architecture level analysis of Ballistic Missile Defense System (BMDS), including neural network based surrogate model.

- Griendling and Mavris (2010): proposed an approach to identifying both system and operational alternatives and then down-selecting a subset of alternatives to

be considered in early-phase design and acquisition for SoS using the Department of Defense Architecture Framework.

- Dahmann et al. (2010): described the distinct characteristics of systems of systems that impact their test and evaluation, discusses their unique challenges, and suggests strategies for managing them. The recommendations are drawn from the experiences of active system of system engineering practitioners.

- Dauby and Upholzer (2011): described an approach utilizing computational intelligence, agent-based modeling and wireless ad hoc network simulation as a computational testbed for exploring the generalized dynamics of complex adaptive systems. It is proposed that the evolutionary algorithm and agent-based model provide the flexibility and autonomy needed to simulate a representative SoS.

- Mekdeci et al. (2011): presented a preliminary examination of how some of the characteristic properties of systems of systems may enable or hinder survivability, based on existing design principles and a newly proposed taxonomy of disturbances.

- Cooksey and Mavris (2011): proposed a game theory approach for modeling a SoS. The proposed approach is used to model smart power grids.

- Lane and Valerdi (2011): analyzed 14 interoperability models and presented two approaches that can be used as an extension to the COSYSMO or COSYSMO for SoS cost models.

- Liu (2011): proposed the design of an emergency management system based on the characteristics of SoS.

- Mostafavi et al. (2011): proposed analysis of system of innovation (SoI) based on the SoS approach.

- Zhou et al. (2011): discussed the issues in SoSE. The existing methods for modeling SoS are reviewed and a computational method for SoS modeling is proposed which could be applied to future production system.

- Eusgeld et al. (2011): discussed the SoS approach to represent interdependencies within critical infrastructures.

- Gezgin et al. (2012): described a modeling approach for SoS in a safety critical context considering its evolutionary nature and focused on the ability to reconfigure the SoS in case of changes of the environment or the SoS itself.

- Han et al. (2012): proposed a conditional resilience metric that measures each constituent system's contribution to overall SoS resilience, and a resilience pattern that shows how SoS performance degrades as systems fail.
- Khalil et al. (2012): proposed a graphical modeling approach for a SoS based on hypergraphs. The architectural representation of hypergraphs is used for model-based supervision of SoS.
- Filippini and Silva (2014): presented a methodology of resilience analysis of systems of systems, with infrastructures as a special instance. A conceptual representation of the infrastructure, based on the functional relationships among its components, is given and then analyzed with respect to its structural and dynamic properties.
- Alexander and Kelly (2013): presented a hazard analysis technique that uses multi-agent modeling and simulation to explore the effects of deviant node behavior within a SoS.
- Darabi and Mansouri (2013): modeled competition and collaboration among constituent elements of a SoS to observe the impact on autonomy and belongingness.
- Pieters (2013): explored the possibility of defining a metric for complex systems, and proposes one in terms of the risk induced by an entity in the system. This also provides a foundation for the notion of "weakest link", in terms of the entity (set of entities) with the highest induced risk.
- Adler and Dagli (2014): presented a study that uses a simple interdependent networked SoS failure model, integrated into a unique objective function that addresses both the overall level of failure and the rate of failure progression, and a genetic algorithm to demonstrate an integrated failure modeling based optimization method to select SoS architectures for improved resiliency.
- Krüger et al. (2010): describes the combination of a model-based approach for distributed system design with aspect-oriented implementation technologies for the purpose of runtime verification. It leveraged the design models, which specify component interactions on logical architectures for testing executable systems against these specifications. The focus of this article is the runtime verification in the systems integration domain; here, Enterprise Service Buses (ESB) have emerged as a powerful infrastructure for integrating complex distributed systems and especially SoS.
- Madni and Sievers (2014): addressed key considerations and challenges in SoSI.

- Harvey and Stanton (2014): This review is intended to extend the reader's understanding of the current state of knowledge of SoS and to exemplify key challenges in terms of a contemporary safety case study.

- Konur and Dagli (2015): studied the process of architecting a System of Systems (SoS) where the SoS architect can negotiate with individual systems.

- Bristow (2015): detailed a resilience assessment project of the city of Toronto with the objective of understanding critical infrastructure interdependencies, to create a platform for stakeholder collaboration on issues related to extreme events, and to improve the city's ability to survive and recover from extreme events efficiently.

- Garro and Tundis (2015): This paper aims at contributing to fill the lack of methods specifically conceived for addressing the analysis and verification of nonfunctional requirements. The attention is focused on system reliability, which is a key requirement to be satisfied particularly for mission-critical systems where system failures could cause even human losses. This paper discusses the specific issues that arise when moving from the reliability analysis of systems to that of systems of systems (SoSs) and proposes a possible extension of the RAMSAS method (called RAMSoS) that is able to address the identified issues and thus support the reliability analysis of SoSs through simulation.

- Bukowski (2016): attempted to generalize the concept of "dependability" in a way, that could be applied to all types of systems, especially SoS, operating under both normal and abnormal work conditions. In order to quantitatively assess the dependability, a service continuity-oriented approach was applied.

- Walewski and Heiles (2016): this paper provided a systematic analysis of SoS architecture models and the relationship of these models with architecture frameworks and how the generalized rules identified can be exploited for the derivation of SoS model kinds.

- Konur et al. (2016): analyzed a SoS architecting problem representing a military mission planning problem with inflexible and flexible systems as a multi-objective mixed-integer-linear optimization model.

- Varga et al. (2017): this paper presents an overview of the arrowhead framework together with its core elements. It provides guidelines for the design and deployment of interoperable Arrowhead-compliant cooperative systems.

- Ed-daoui et al. (2018c): this paper details a structural deterministic approach to quantitatively measure systems resilience. This approach is based on a three-step method. The first step is to evaluate the functional dependencies between groups by considering a SoS as a large-scale interconnected network of systems distributed into interdependent groups. This leads to better understand the overall connections and process continuity. Next step is to analyze how much the global architecture of the SoS depends on every group. And the last step is to estimate its structural resilience by measuring the impact of each system's failure on the other systems forming the global system and building the process.

- Ed-daoui et al. (2019a): it proposes two complementary approaches in an attempt to contribute to SoS (SoS) safety evaluation through resilience assessment. The first approach is a risk monitoring design, it is conceived to monitor, evaluate and analyze risks that represent destabilizations' catalyzers. The second one is a structural analysis that begins with the estimation of criticality and frailty levels which leads to the calculation of failure impact and susceptibility measures of a CS on/to the SoS performance and process continuity. The combination of these approaches helps to assess SoS resilience through building a futurist, quantitative and anticipative perspective to evaluate the potential risks, their influences and impacts on SoS structure.

2.4 SoS Standards

In engineering, standards and standardization are being considered as "universally agreed-upon set of guidelines" Johnson and Jamshidi (2009). There are four levels of standardization: compatibility, interchangeability, commonality and reference Johnson and Jamshidi (2009).

These standardization levels are relevant in an SoS environment since they contribute to "compatibility, similarity, measurement symbol, and ontological standardization" Jamshidi (2008b). There is a need for standards' development in order to ensure meeting SoS standardization levels.

Growth of information technologies and requirements for globalization drive the need for new standards. The more the SoS integrates heterogeneous components, the more there is a need for harmonization.

2.4.1 Current Frameworks and Standards

Zachman Framework

The Zachman Enterprise Framework was invented by John Zachman in 1980 for IBM, and is now in the public domain. The framework borrows from business design principles in architecture and manufacturing and provides a way of viewing an enterprise and its information systems from different perspectives, and showing how the components of the enterprise are related.

In today's complex business environments, many large organizations have great difficulty responding to change. Part of this difficulty is due to a lack of internal understanding of the complex structure and components in different areas of the organization, where legacy information about the business is locked away in the minds of specific employees or business units, without being made explicit.

The Zachman framework helps to classify an organization's architecture. It is a proactive business tool, which can be used to model an organization's existing functions, elements and processes - and help manage business change. The framework draws on Zachman's experience of how change is managed in complex products.

Although the framework can be used for information systems architecture (ISA) and is widely adopted by systems analysts and database designers, John Zachman has stressed that it extends to the entire enterprise architecture and is not restricted to simply information architecture.

The Zachman enterprise framework is represented and promoted by the ZIFA (Zachman Institute for Framework Advancement) organization. It is not viewed as a standard and there are similar enterprise frameworks that have been derived from it, such as the Federal Enterprise Architecture Framework (FEAF), The Open Group Architecture Framework (TOGAF), and the Department of Defense Architecture Framework (DoDAF).

The framework provides a consistent and systematic way of describing an enterprise and has been employed in many large organizations, such as Volkswagen, General Motors, Bank of America and Health Canada.

Department of Defense Architecture Framework

DoDAF (Department of Defense Architecture Framework) is a creation of the United States DoD (Department of Defense). It aims to provide semantic and syntactic

interoperability standards.

It provides visualization infrastructure for specific stakeholders concerns through viewpoints, organized by various views. These views are artifacts for visualizing, understanding and assimilating the broad scope and complexities of an architecture description through tabular, structural, behavioral, ontological, pictorial, temporal, graphical, probabilistic, or alternative conceptual means.

The DoDAF provides a foundational framework for developing and representing architecture descriptions that ensure a common denominator for understanding, comparing, and integrating architectures across organizational, joint, and multinational boundaries. It establishes data element definitions, rules, and relationships and a baseline set of products for a consistent development of systems, integrated, or federated architectures. These architecture descriptions may include families of systems (FoS), SoS and net-centric capabilities for interoperating and interacting in the non-combat environment.

The purpose of DoDAF is to define concepts and models usable in DoD's six core processes:

- Joint Capabilities Integration and Development (JCIDS)
- Planning, Programming, Budgeting, and Execution (PPBE)
- Defense Acquisition System (DAS)
- Systems Engineering (SE)
- Operational Planning (OPLAN)
- Capability Portfolio Management (CPM)

In addition, DoDAF 2.0's specific goals were to:

- Establish guidance for architecture content as a function of purpose "fit for purpose"
- Increase utility and effectiveness of architectures via a rigorous data model the DoDAF Meta Model (DM2) – so the architectures can be integrated, analyzed, and evaluated with more precision.

In DoDAF v2.0, architectural viewpoints are composed of data that have been organized to facilitate understanding. To align with ISO Standards, when appropriate, the terminology has changed from Views to Viewpoint:

- **All Viewpoint (AV):** Describes the overarching aspects of architecture context that relate to all viewpoints.
- **Capability Viewpoint (CV):** New in DoDAF V2.0. articulates the capability requirements, the delivery timing, and the deployed capability.
- **Data and Information Viewpoint (DIV):** New in DoDAF V2.0. Articulates the data relationships and alignment structures in the architecture content for the capability and operational requirements, system engineering processes, and systems and services.
- **Operational Viewpoint (OV):** Includes the operational scenarios, activities, and requirements that support capabilities.
- **Project Viewpoint (PV):** New in DoDAF V2.0. Describes the relationships between operational and capability requirements and the various projects being implemented. The Project Viewpoint also details dependencies among capability and operational requirements, system engineering processes, systems design, and services design within the Defense Acquisition System process.
- **Services Viewpoint (SvcV):** New in DoDAF V2.0. Presents the design for solutions articulating the Performers, Activities, Services, and their Exchanges, providing for or supporting operational and capability functions.
- **Standards Viewpoint (StdV):** Renamed from Technical Standards View. Articulates the applicable operational, business, technical, and industry policies, standards, guidance, constraints, and forecasts that apply to capability and operational requirements, system engineering processes, and systems and services.
- **Systems Viewpoint (SV):** Articulates, for legacy support, the design for solutions articulating the systems, their composition, interconnectivity, and context providing for or supporting operational and capability functions.

NATO Architecture Framework

The North Atlantic Treaty Organization (NATO) aims to provide a standard for developing and describing architectures for both military and business use. It provides a standardized way to develop architecture artifacts.

The NATO Architecture Framework v4 (NAFv4), issued by the Architecture Capability Team (ACaT) of the NATO Consultation, Command & Control Board

(C3B) in January 2018, provides guidance on describing both Enterprise Architectures and Systems Architectures.

The objectives of the framework are to:

- Provide a way to organize and present architectures to stakeholders
- Specify the guidance, rules, and product descriptions for developing and presenting architecture information
- Ensure a common approach for understanding, comparing, and integrating architectures,
- Act as a key enabler for acquiring and fielding cost-effective and interoperable capabilities
- Align with architecture references produced by international standard bodies (International Organization for Standardization, Institute of Electrical and Electronic Engineers, The Open Group, Object Management Group, etc.)

2.5 An Overview of the Reliability Concept

The concept of reliability has grown and evolved since its first use by the English poet of the romantic school Samuel T. Coleridge, when he wrote in praise of his friend the other poet Robert Southey in Coleridge (2015):

"He inflicts none of those small pains and discomforts which irregular men scatter about them and which in the aggregate so often become formidable obstacles both to happiness and utility; while on the contrary he bestows all the pleasures, and inspires all that ease of mind on those around him or connected with him, with perfect consistency, and (if such a word might be framed) absolute reliability."

The reliability concept became a more generalized and pertinent attribute for all kinds of systems evaluation Ed-daoui et al. (2017b). Therefore, numerous definitions were proposed to sire this concept. We present some of the numerous definitions of reliability:

- **Birolini Alessandro**: "Reliability represents the probability that the item will perform its required function under given conditions for a stated time interval" Birolini (2013).

- **Mellor Peter**: "Reliability is the ability of a system to deliver its required service under given conditions for a given time" Mellor (1992).
- **Zio Enrico**: "Reliability is a fundamental attribute for the safe operation of any modern technological system" Zio (2009).
- **Saleh Joseph H. and Ken Marais**: "Reliability is a popular concept that has been celebrated for years as a commendable attribute of a person or an artifact" Saleh and Marais (2006).
- **Katina Polinpapilinho F. and al.**: "It is the probability that a system will perform its intended mission(s) when called upon to do so" Katina et al. (2014), Katina et al. (2016).

2.5.1 Reliability Assessement Approaches Taxonomy

With the increasing complexity of systems having a multi-dimensional character as structure, in addition to the growing levels of uncertainty and risk, the exploitation of classic methods of assessing reliability has become insufficient Bukowski (2016).

Therefore, in order to approach reliability, especially in a SoS context, there are three main approaches based on mathematical models:

- Probabilistic approaches
- Statistical approaches
- Deterministic approaches

The probabilistic approaches for reliability calculations are prognostic. They are about the probability that a system will perform as required under some conditions during a time interval. And in the calculation, probabilistic manners and methods, along with random variables and attributes, are utilized in order to cast the value.

In probabilistic approaches, the events can be identified through their probabilities of occurrence. Besides, a complete analysis of the systems insinuates a dependent probability for risk definition and prognostic estimation of consequences. The conditions under which the experiment is observed will only determine a probabilistic behavior of the observable outcome.

Statistical approaches are mathematical formulas, models, and techniques that are used in statistical analysis of raw research data. The application of statistical

methods extracts information from research data and provides different ways to assess the robustness of research outputs.

They are descriptive approaches in which a great number of similar events hold experimental values. The analysis of a great number of directly usable observations on the level of systems/events.

Deterministic approaches in which outcomes (whether numerical or otherwise) are precisely determined through known relationships among state, events and conditions under which the experiment is carried out, without any room for random variation. In such models, a given input will always produce the same output, such as in a known chemical reaction.

They are definitive approaches where the effects analyze of assumed causes on the level of relevant systems and events. Events are completely predetermined through effect chains. This insinuates causality.

In this thesis, deterministic approaches are proposed to assess SoS resilience through structural analysis. The idea is to bridge the gap between resilience and reliability through structural analysis.

2.6 Resilience in the SoS Context

Actually, the concept of resilience is difficult to interpret, especially in SoS context. It is generally defined as the capacity of a system to recover after disturbances. There is a growing consensus that a resilient system is capable to achieve its intended purpose under the full range of conditions Jamshidi (2008b).

In some literature, resilience represents an important concept to tackle SoS reliability and safety along with survivability and trustworthiness Avizienis et al. (2004), Bukowski (2016), Ed-daoui et al. (2018c), Ed-daoui et al. (2016b), Ed-daoui et al. (2016a), Ed-daoui et al. (2017b), Mansouri et al. (2009b), Saleh and Marais (2006), Sherrieb et al. (2010), Tran et al. (2016a) Tran et al. (2016a), Ben Yaghlane and Azaiez (2017).

In fact, if an unpredictable event occurs to a system, the resilience represents its capacity to restore Aven (2011), Mansouri et al. (2009b). It concerns the consequences in case of risk and inherent uncertainties.

An interdisciplinary discussion has been developed about how designers can incorporate resilience into the engineering of complex systems in general and especially

in SoS. Other researchers from different domains have also analyzed the concept of resilience in an attempt to lead the effort behind shedding the light on it: Ecological systems Holling (1973), Safety engineering Woods (2006), critical infrastructures Ed-daoui et al. (2018c), Filippini and Silva (2014), Turnquist and Vugrin (2013), Alderson et al. (2015), communication networks Sterbenz et al. (2013), logistics and transportation networks Ip and Wang (2011), Zhao et al. (2011) and organizational resilience Mendonça and Wallace (2015), Woods (2006).

This section gives a brief overview of prominent resilience definitions. Following this overview, relevant frameworks and metrics for assessing resilience are discussed.

2.6.1 Resilience Definitions

Much of the early work focusing on resilience has been about proposing definitions and common properties of resilient systems. They appear within various scientific fields and are often tailored to specific applications of interest Tran et al. (2017).

Therefore, to get a holistic view of resilience, a review insight from various disciplines will briefly be detailed. Although it is not the intent to provide an in-depth review of such diverse literature, there will be some referencing to some definitions in an attempt to identify those commonalities.

Resilience is defined as the system's ability to continue operations or recover a stable functional state after a major mishap or event. Furthermore, it represents the system's capability to prevent or to adapt to changing conditions in order to maintain system property(ies) Leveson et al. (2012). However, this definition of resilience can hardly be distinguished from robustness, which represents the system's ability to maintain its function within a controlled tolerance under disturbances Zang et al. (2005), Wang et al. (2010).

Another definition of resilience has been proposed in Han et al. (2016), it is seen as a system's property that can still function to the desired level when the system suffers from partial damage. A more generalized definition has also been proposed in (Merriam-Webster Online Dictionary) Ozgur et al. (2010). It is defined as the ability to recover from or adjust easily to misfortune or change.

Even in psychology, a definition of resilience has been proposed. It has been characterized as the positive capacity of individuals to cope with stress and catastrophic events and their level of resistance to future negative events Ozgur et al. (2010). While in computer networks, resilience has been expressed as the ability to provide and maintain an acceptable level of service in the face of faults and challenges

to normal operations Hollnagel et al. (2006).

Considering discussions of resilience from a variety of communities, the common aspect of all these definitions is that resilience is defined as a response to unexpected or unforeseen changes and disturbances, as well as the ability to adapt and respond to such changes Ed-daoui et al. (2018c), Ozgur et al. (2010).

2.6.2 Literature Overview

Resilience Engineering is an emerging discipline Hollnagel et al. (2006) which aims to enhance an organization's ability to target safety investments proactively in the face of ongoing production and economic pressures Woods (2006). Methods and metrics for quantitatively assessing resilience are also proposed to enable rigorous and traceable comparisons between potential system designs. Several quantitative assessment methods have been proposed in the literature Tran et al. (2017).

In Reed et al. (2009), a method to characterize the behavior of networked infrastructure for natural hazard events and improve infrastructures resilience is proposed. It includes resilience and interdependency measures. Authors focused their study on the contribution of power delivery systems to post-event infrastructure recovery. The model is a component of a scheme that develops design strategies in order to increase the resilience of infrastructures for extreme natural hazard scenarios.

The goal is to capture the recovery aspects to identify the trends in interconnections in order to assist others who are developing the intricate models and databases required for regional planning and evaluation.

A framework for resilience engineering is proposed in Madni and Jackson (2009). Authors define resilience from different perspectives and provide a conceptual framework dedicated to analyzing disruptions. They present principles for the creation of resilient systems. It includes disruptions, system attributes, methods and metrics. The idea behind such classification is to allow systems engineers to focus on what the impacted attributes are whenever resilience is needed and what methods are appropriate to achieve resilience.

They began by emphasizing that there is a reflex of misattributing systems failure and mishaps occurrence to human error. They also proposed clarification of the difference between safety, reliability, survivability and resilience. Accordingly, they have emphasized that resilience engineering does not see failure as a breakdown, but, it is viewed as an inability of the system to either absorb perturbations or adapt to changes in real-world conditions.

In Filippini and Silva (2014), an infrastructure resilience-oriented modeling language (IRML) is proposed to facilitate the analysis of operational interdependencies of infrastructure's components, resilience, the ability to withstand risks and recover.

The IRML comes with a set of analysis tools and procedures that investigate structural properties and resilience. Its analysis leads to a screening of structural and dynamic properties that are related to the SoS resilient behavior, in order to provide additional insights about possible misbehaviors at a large-scale.

In Zhang and Lin (2010), the authors define some principles to enhance enterprise information systems' resilience. They propose an architecture of what they call "resilient enterprise information systems". It is elaborated on a particular identity of resilience which is related to humans as it is implicated in its safety and health.

Authors see that resilience has roots in biological and ecological systems which leads to derive the proposed five design principles for resilient systems. These design principles are well applicable to enterprise information systems in order to be resilient.

2.6.3 The Correlation between Resilience and Reliability

SoS need to be reliable, to preserve the same performance, to complete the required functions and most importantly to be capable of anticipating as many defects as possible. The relationship with resilience is among the numerous approaches to tackle reliability in the context of SoS.

Resilience is defined as the ability of systems to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time, composite costs and risks. Reliability and resilience concepts are two strongly related notions. This is emphasized by recent literature Avizienis et al. (2004), Ed-daoui et al. (2018c), Birolini (2013).

In this thesis, the strength of the correlation between resilience and reliability are leveraged. The aim is to emphasize the mutual correspondence between the two concepts. Resilience evaluation and assessment imply the implicit evaluation and assessment of reliability.

2.6.4 The Position Towards Literature

In Figure 2.4, four SoS research areas are shown, namely, concept, modeling and applications. The SoS has caught the attention of the research community; therefore,

numerous works contributed to develop SoS principles and analyze their properties.

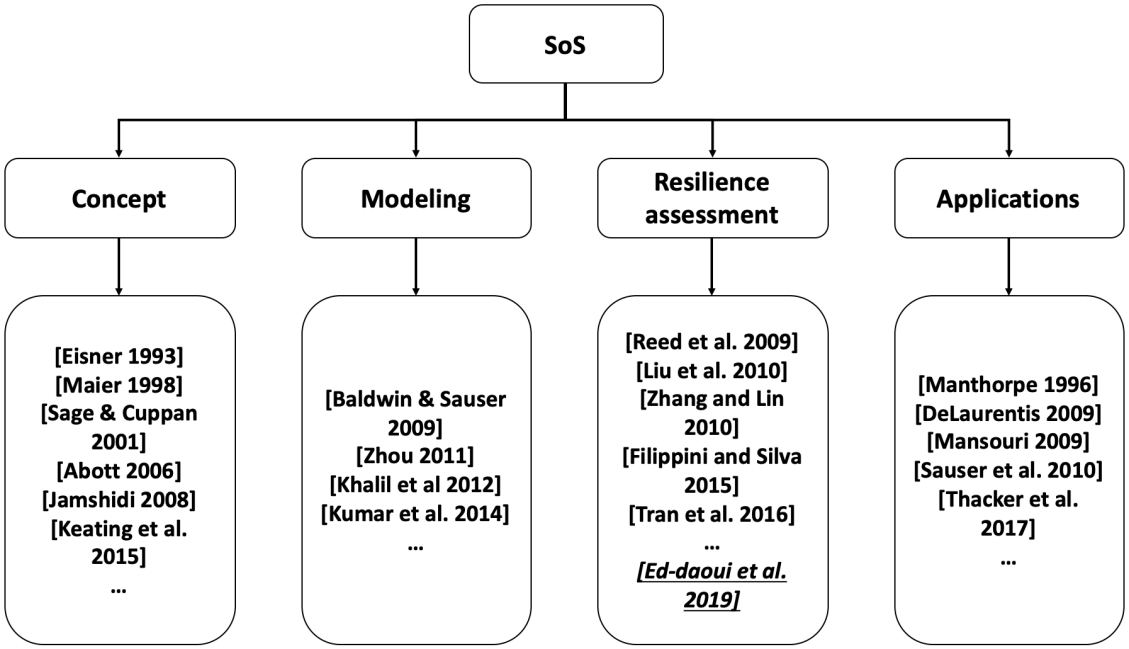

Figure 2.4: Contribution positioning towards SoS literature. Adapted from Kumar (2014).

Table 2.4 summarizes the contribution and situates the works elaborated during the preparation of this thesis with regards to the current literature. As illustrated, there is a need for further development in some aspects such as risks management, structural analysis, monitoring, resilience quantification and their influence on SoS reliability. This thesis proposes answers to this demand.

In order to fully assimilate the proposed work in this thesis, it is crucial to be positioned in a structural standpoint. The idea is to be able to differentiate two complementary aspects embracing the concept of SoS which are the dynamic and the static aspects.

The dynamic aspect of SoS is related to its extensibility. The structure of the SoS is in constant evolvement and change. Therefore, the evolutionary model of SoS provides a dynamic to the structure. And it is a particularity that distinguishes SoS from systems as classically understood.

As in this thesis, the major focus is to assess the structural resilience of SoS, it is utterly inevitable to take this aspect into account. Thus, an interoperability assessment approach is proposed in order to be able to assess the structural resilience

	Risk analysis	Structural analysis	Resilience quantification and measurement	Interoperability	Reliability	Recovery
Reed et al. (2009)		x	x			x
Filippini and Silva (2014)		x				x
Zhang and Lin (2010)					x	
Tran et al. (2017)			x			x
Liu et al. (2010)		x			x	
Wang et al. (2010)			x			
This thesis	x	x	x	x	x	

Table 2.4:: Literature positioning towards different aspects siring the concept of resilience.

with regards to SoS dynamics.

On the other hand, if the structure of SoS is captured in a random or chosen instant, it will look like a fixed SoS composed of a certain quantity of CS, linked by a fixed number of interdependencies with precise workflow pathways and under in a static condition and environment, etc.

Therefore, from this perspective, the SoS can lose its dynamic and be perceived as a static object. And in order to have a complete structural study of the SoS structural resilience, it is also important to assess the static aspect of SoS structure. In this thesis, a static structural resilience assessment approach based on mathematical equations and a set of indicators is proposed as a response to particularity.

Eventually, both proposed approaches are deterministic and can be used to evaluate the actual state of SoS structure or to anticipate its resilience in some scenarios that could probably occur in the future.

Accordingly, this work also contributes to the demand for SoS structural reliability assessment and enhancement. The resilience assessment implies the implicit

assessment of reliability.

2.7 Conclusions

To sire the broad scope of SoS is a tremendous challenge. Whereas, the inherent and growing need for the exploitation of such systems, as well as the rapidly increasing costs incurred by loss of operation as a consequence of failures, stimulate some serious resilience and reliability concerns.

Nowadays, we expect more of a SoS than just to be functional and free from failures and defects in the implementation phase but also to enhance its reliability level, to preserve the same performance, to complete the required functions and most importantly to anticipate as many defects as possible in the architecting phase Aggarwal (1993), Han et al. (2012), Xia et al. (2016).

The presented review shows that literature lacks works dedicated to fully address the resilience of SoS through structural analysis.

In remaining part of this thesis, two complementary approaches are proposed in an attempt to analyze SoS structural resilience. First is related to extensibility which is a specific characteristic of SoS as they are in continuous evolvement and change. A major focus is to evaluate SoS structural resilience with regards to its dynamic aspect and through interoperability assessment. On the other hand, a consideration of the SoS structure and inner workflow pathways represents the second approach. This perspective leads to structural resilience assessment through a set of indicators. Both proposed approaches are deterministic and can be used to evaluate the current state of a SoS structure or to anticipate its resilience in future scenarios.

A prototype is designed in order to process the structural resilience assessment. Considering spatial objects, it has been used to conduct experiments on real-based industrial infrastructures approached as SoS.

Chapter 3

SoS Structural Interoperability Assessment

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3.1 Introduction

Generally speaking, interoperability is a quality and not a characteristic of a system, and it must be defined for at least a pair of systems by decision-makers in the conceptual design phase. In addition, it can be considered as a metric dedicated to architecture's evaluation Han et al. (2012).

It represents the ability of connected, autonomous, coupled and heterogeneous systems to collaborate and to interoperate while preserving their own autonomy and their own logic Aggarwal (1993).

In this section, a brief overview of interoperability-related literature is presented. The idea is to put the reader in the perspective of interoperability before demonstrating its propitiousness to the diagnose of the interdependencies forming the basic structure of the SoS in addition to its utility to evaluate, quantify, analyze and sometimes anticipate the structural operability between CS.

In Aggarwal (1993), authors conceptually assimilate a coalition of enterprises collaboration, which they called a collaborative network of organizations, as a SoS presenting a number of characteristics to respect all over its life cycle.

They consider interoperability as an essential characteristic, among others, to ensure the control of SoS, including their performance and fulfillment of their missions. In addition, they see that interoperability helps to anticipate the reaction of a SoS dealing with some risky situations with potential local or global deficits during its functioning.

Thus, they examine the relationship between SoS interoperability and functioning, whatever the situation. A matrix is used to track the evolvement occurring in the SoS, especially its capacity to respect interoperability requirements, which are compatibility, interoperation, autonomy and reversibility in addition to the performance, integrity and stability.

An analysis of fourteen interoperability models and presentation of two approaches that can be used as an extension to the COSYSMO for SoS cost models are proposed in Tsilipanos et al. (2013). Authors consider interoperability as a characteristic, among others, of SoS that enables the flow of information and the seamless introduction of new CS into the SoS. However, it always comes at a price.

They see that the assessment of interoperability is an important step towards optimal resource planning, as it is also important to quantify the levels of interoperability difficulty. Their objective was to incorporate interoperability considerations into cost models so that planners can accurately forecast its impact on project exe-

cution. This approach can be extended to cover project execution tracking.

Authors of Han et al. (2012) consider the interoperability as a metric of architecture that must be understood by decision makers as early as the conceptual design phase. Their objective is systems interoperability measurement within a potential architecture performing a set of resource exchanges while relying on reliability to link interoperability to performance metrics. For that purpose, they consider the reliability of a pair of CS performing a resource exchange as the probability that the resource exchange will meet performance requirements.

In Deleuze et al. (2013), a practical framework for modeling the behavior of a complex system, in terms of structure, and dynamic interactions between subsystems and components is proposed, which is named the dynamic reliability approach. Authors explain how a meta-model defines a framework for integrating security into systems engineering processes. In addition, they propose a meta-model that supports a "hub automaton" or "pivot automaton", which is a key element for interoperability analysis among other tools and activities required for a dynamic reliability assessment.

Therefore, Interoperability is a quality that can be viewed from various perspectives. Consequently, an illustrative classification of interoperability axes is detailed. It represents the adopted perspective to handle interoperability. It embraces barriers, scopes and levels.

In the following sections, an approach dedicated to SoS structural operability assessment is detailed. It aims to analyze the SoS structural resilience through interoperability assessment with consideration to the dynamic of the structure. This aspect is strongly related to a special characteristic of SoS, it is called extensibility. It is due to their continuous evolvement and change.

A set of indicators is included in this approach. They will be presented and detailed posteriorly. They are based on interoperability and exchange inefficiency assessments. The idea is to analyze and evaluate the structural operability of the existing interdependencies, with interdependencies representing links between CS within the SoS.

The remaining part of this chapter is organized as follows:

- Section 2 introduces a classification of interoperability including three important axes for SoS structural assessment.
- Section 3 details the second metric necessary for a better assessment of interoperability in the SoS context, which is the inefficiency of exchange.
- Section 4 explains the correlation between the interoperability assessment and

the structural analysis.

- Applications of the theory to real-based case studies are presented in section 5.
- Section 6 proposes a model designed by UML for an eventual implementation.
- The last section draws conclusions.

3.2 Interoperability Assessment

From a SoS perspective, CS are considered as autonomous in terms of their functionality and operation, and heterogeneous in terms of their nature. They collaborate with each other so as to achieve the SoS objectives.

Furthermore, in order to compare and contrast multiple and heterogeneous CS, a consistent description of interoperability, regardless of the implementation environment, must be developed. Therefore, there is a tremendous need to assess interoperability among those CS in order to recognize and overcome compatibility issues caused by their heterogeneous nature Billaud et al. (2015).

Interoperability is a quality that can be viewed from various perspectives. Therefore, a proposition of an illustrative classification of interoperability is depicted in Figure 3.2. In this taxonomy, three important axes for SoS interoperability assessment need to be handled:

- **Interoperability Levels:** they are inherent to the diversified natures of relationships between CS within the SoS. Four levels of interoperability are defined: business, process, service and data.
- **Interoperability Barriers:** they represent the nature of the circumstance(s) or obstacle(s) that may disturb, interrupt or even put an end to an interaction between two (or more) CS. Four barriers categories are defined: organizational, functional, geographical and technical barriers.
- **Interoperability Scopes:** as SoS may also interact, two different possibilities are recognized. First is the internal scope which is concerned when interactions between CS are amid the same SoS. Second if the external scope, it concerned when two (or more) CS from different SoS interact.

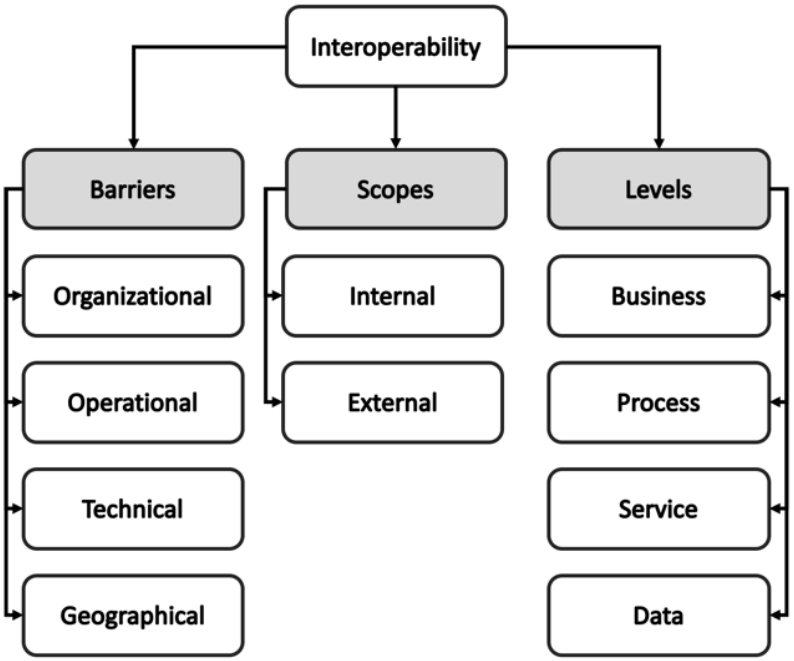

Figure 3.1: Interoperability Classification. Source: Ed-daoui et al. (2019c).

3.2.1 Interoperability Levels

In order to assess interoperability, and especially in SoS context, means must be developed to characterize multiple CS and signify where they fall within the interoperability's general definition.

To accomplish this, a set of increasingly sophisticated "levels" of interoperability are elucidated. Each level represents a specific characterization of various elements and the associated set of capabilities present to stimulate interoperability. A level of interoperability is defined as a composite of the four different features described below.

The concept of levels inspired by LISI (Levels of Information Systems Interoperability) and the maturity models Group et al. (1998).

- **Data level:** In SoS, CS have tendency to be autonomous and heterogeneous. This fosters an enormous challenge for data and information standardization as they may come from heterogeneous sources. Thus, it is crucial to handle the exchange, interpretation and exploitation of data in addition to information management within the SoS.
- **Service level:** This concerns the conception, exploitation, identification and

evaluation of functions and the execution of numerous services or applications that need to be designed and implemented independently but perform coactively.

- **Process level:** Its aim is to evaluate the different collaborating processes. In case of networked enterprises, it is about interconnected processes of interacting companies in order to assess the achievement of a target. The latter needs to have a contribution to the achievement of the system(s)-of-systems target(s).
- **Business level:** This is involved in case of networked companies. Its aim is to evaluate the shared and developed common business. This may have some trammels as different working practices, legislation, decision making, cultures of companies, etc.

These levels are useful in the evaluation of the severity of barriers that threaten the interdependencies relating CS. The definition of different layers to analyze interconnections relating CS and capabilities helps to locate the trammels. Therefore, interventions to overcome them become more pertinent. This contributes to the structural analysis of the global system.

3.2.2 Interoperability Barriers

Using interoperability levels, barriers assessment becomes more sophisticated and prevalent. Furthermore, for better structural analysis and consequently better barriers evaluation, a classification of barriers would be utilitarian.

In fact, barriers, as their name indicates, represent any obstacle that would possibly disturb, interrupt or even put an end to interactions between CS through interdependencies.

A classification of interoperability barriers is proposed. It is based on four categories inspired by the topology presented in Jones-Wyatt et al. (2013), where authors propose a classification of three categories: organizational, conceptual and technical barriers. The proposition is adopted and extended by adding another category of barriers called: "geographical barriers". Here is a presentation of each category:

- **Organizational barriers:** This class defines the structural arrangement of the CS within the SoS, especially if they are companies. These barriers concern human, legislative, decisional, and financial barriers, commercial approaches and the culture of an enterprise that can discommode interoperability, as well as the interactions between systems.

- **Functional barriers**: This feature defines the statement of need between two CS planning to exchange data, information, documents, etc. They are related to the incompatibility of procedures and norms or standards to present and communicate information, as well as the methods of work and technical incompatibilities that may perturb the interactions and interoperability of communicating systems.

- **Technical barriers:** This represents the rules and criteria that govern the implementation of the systems and support interactions amid the SoS. These criteria include standards and conventions, specific product-based solutions, and gateways that technically describe a specific capability. Two classes of technical barriers are proposed: logical and physical. Logical barriers are related to exploited software, programs, solutions, services, etc. and physical barriers are related to the physical structure supporting the logical solutions.

- **Geographical barriers:** This represents the geographical context that embraces the implementation of the SoS. These barriers represent anything that blocks the pathway between two systems. This can be any natural feature such as mountains or even natural disasters that prevent the interaction from being successful.

By design, interoperability levels and barriers provide guidance for structural analysis through three interrelated views, so as to map imperfections and irregularities in order to evaluate and enhance SoS performance.

In order to improve interoperability, there must be a known basis for making changes. The use of this approach in support of the structural development and in response to implementing the resulting structure is key to developing this basis.

If a CS implementation is to be successful within a SoS, it must include and clearly reference the requirements and current conditions of interoperability that are present within the structural analysis.

3.2.3 Barriers Evaluation

The evaluation of barriers is done through a set of matrices inspired by Lane and Valerdi (2011). Each matrix concerns a class of barriers. The evaluation is done for each aspect of the barriers classes under the aegis of the four levels of interoperability.

In practical terms, each aspect of organizational, functional, technical and geographical barriers is evaluated by virtue of interoperability levels (Business, Process,

Service and Data). Therefore, if an aspect has a barrier or an obstacle that prevents the interaction or the interoperability, the value *1* is assigned to the corresponding slot in the matrix. Contrarily, the value *0* is assigned in case there are no barriers.

	Human	Legislation	Finance	Decision making	Commercial approach	Culture of enterprise
Business	do_{11}	do_{12}	do_{13}	do_{14}	do_{15}	do_{16}
Process	do_{21}	do_{22}	do_{23}	do_{24}	do_{25}	do_{26}
Service	do_{31}	do_{32}	do_{33}	do_{34}	do_{35}	do_{36}
Data	do_{41}	do_{42}	do_{43}	do_{44}	do_{45}	do_{46}

Table 3.1:: Organizational matrix illustration.

In Table 3.1, the elementary value of each organizational barrier is noted by do_{ij} (with $i \in \{1, 2, 3, 4\}$, and $j \in \{1, 2, 3, 4, 5, 6\}$). The value of the organizational barriers, noted DO, is calculated as shown in formula 3.1.

$$DO = \sum_{j=1}^{6} \sum_{i=1}^{4} \frac{do_{ij}}{24} \tag{3.1}$$

	Procedure	Norms and standards	Method of work	Technological
Business	df_{11}	df_{12}	df_{13}	df_{14}
Process	df_{21}	df_{22}	df_{23}	df_{24}
Service	df_{31}	df_{32}	df_{33}	df_{34}
Data	df_{41}	df_{42}	df_{43}	df_{44}

Table 3.2:: Functional matrix illustration.

Accordingly, in Table 3.2, df_{ij} corresponds to the value of each slot in the matrix functional barriers (with $i \in \{1, 2, 3, 4\}$, and $j \in \{1, 2, 3, 4\}$). The value of the functional barriers noted DF is calculated as shown in formula 3.2.

$$DF = \sum_{j=1}^{4} \sum_{i=1}^{4} \frac{df_{ij}}{16} \tag{3.2}$$

Correspondingly, in Table 3.3 and Table 3.4, dt_{ij} and dg_i correspond to the values of each slot (respectively) in both the technical barriers matrix and the geographic

	Logical	Physical
Business	dt_{11}	dt_{12}
Process	dt_{21}	dt_{22}
Service	dt_{31}	dt_{32}
Data	dt_{41}	dt_{42}

Table 3.3:: Technical matrix illustration.

	Geographical barriers
Business	dg_{11}
Process	dg_{21}
Service	dg_{31}
Data	dg_{41}

Table 3.4:: Geographical vector illustration.

barriers vector. The values of the technical and geographical barriers, noted respectively DT and DG, are calculated as shown in formula 3.3 and formula 3.4.

$$DT = \sum_{j=1}^{2} \sum_{i=1}^{4} \frac{dt_{ij}}{8} \tag{3.3}$$

$$DG = \sum_{i=1}^{4} \frac{dg_i}{4} \tag{3.4}$$

Eventually, as DO, DF, DT and DG, that return the rate of barriers in each class of barriers, are independent and there is no overlapping between them. The arithmetic form of mean is chosen for the calculation of the global barriers degree as depicted in formula 3.5.

$$DB = \frac{DO + DF + DT + DG}{4} \tag{3.5}$$

3.3 Exchange Inefficiency

A second metric that we propose for the completion of the interoperability assessment is the inefficiency of exchange. It aims to evaluate the exchange within the global

system. This is done through three aspects related to the exchange and its inefficiency, they are called *The three Fs*:

- The failure rate of exchange
- The failure of interpretation
- The flouting

The failure rate represents the rate of unsuccessful exchanges. It is calculated by dividing the number of unsuccessful exchanges by the total number of exchanges, as depicted in formula 3.6. Exchanges here refer to all data, information, documents, etc. exchanged through an interaction or an interdependency between at least two CS, two capabilities or a CS and a capability.

$$F_r = \frac{n_{uns}}{n_{tot}} \tag{3.6}$$

With:
F_r: represents the failure rate of exchanges.
n_{uns}: stands for the number of unsuccessful exchanges.
n_{tot}: stands for the total number of exchanges.

The failure of interpretation represents the rate of unsuccessfully interpreted information, data, or anything generated by a CS or a capability and transferred to (an)other CS(s) or capability(ies). It is calculated by devising the number of unsuccessfully interpreted information by the total number of exchanges. See formula 3.7.

$$F_{int} = \frac{n_{int}}{n_{tot}} \tag{3.7}$$

With:
F_{int}: represents the failure of interpretation.
n_{int}: represents the number of unsuccessfully interpreted information, data, or anything generated by a system of a capability and transferred to (an)other system(s) or capability(ies).
n_{tot}: stands for the total number of exchanges.

The flouting represents the rate of nonconforming information, data, documents or anything generated by a system of a capability and transferred to (an)other system(s) or capability(ies). It is calculated by devising the number of nonconforming information upon the number of the total information received. See formula 3.8

$$F_{fl} = \frac{n_{nconf}}{n_{tot}} \tag{3.8}$$

With:
F_{fl}: represents the flouting. n_{nconf}: represents the number of nonconforming/flouting exchanges. n_{tot}: stands for the total number of exchanges.

Eventually, there is the inefficiency of exchange, which represents the rate of the overall rates of irregularities in exchange within the SoS that are represented by the arithmetic mean of the three Fs. The arithmetic form of mean is chosen because the three aspects of the exchange inefficiency (failure rate, failure of interpretation and flouting) are independent and there is no overlapping at any time between them. See formula 3.9.

$$EI = \frac{F_r + F_{int} + F_{fl}}{3} \tag{3.9}$$

3.4 Interoperability Assessment as a Basis to SoS Structural Analysis

SoS assessment remains a tremendous challenge, and it is not only due to SoS complexity and size; the interdependencies relating CS and inherent interoperability are what affect, for the most cases, the behavior of the whole SoS Xia et al. (2016),Deleuze et al. (2013).

This work is a response to the need for metrics to support decision making regarding the organization of structures amidst SoS. It is based on SoS structural analysis through interoperability assessment. It aims to provide metrics so as to evaluate the effect of topology and interdependencies degraded functioning on both operability and SoS structure.

Practically, the previously mentioned metrics (DB and EI) are both used in one formula in order to deduct another measure, called structural operability indicator (SOI). SOI contributes to the evaluation of the health of the global system's structure by means of the interdependencies' operability rates.

The return of the SOI metric is the rate of the operability of a coalition of interdependent CS by considering its exposition to the threats which are approached as barriers in addition to the exchange inefficiency. The SoS operability calculation is tackled by structural assessment which is endorsed by a calculative perspective of disturbances. The disturbances, considered in our calculation, are those targeting interoperability. The calculation process should be applied, similarly, on every single interdependency based on the system's structure, as depicted in formula 3.10. It should be noted that the structural operability indicator returns the rate of the interdependency's operability.

$$SOI = 1 - \sqrt{DB \times EI} \tag{3.10}$$

The idea behind considering disturbances in both barriers degree and exchange inefficiency is to be able to assess the interdependency's capability to operate under the considered circumstances. This explains the appellation of the metric.

The more there is disturbances, the more there is chances that SoS resilience and operability may degrade. Accordingly, the structural operability indicator calculates the rate of the operability amidst SoS with the consideration of the disturbances mean.

Another reason behind the formulation of the proposed structural operability equation is that both barriers and exchange inefficiency may be inseparably responsible for the SoS's lack of efficient operability.

This is an attempt to develop a method to measure the interoperability in the SoS context. The proposed metrics converge towards the structural operability indicator that contributes to the assessment of SoS structure through interoperability evaluation.

In the following section, an application of the explained theory will be presented. A comparison between the proposition and the approach in Lane and Valerdi (2011) is also included. The case studies are based on reality.

3.5 Application to Case Studies

In this section, an application of the theory to two case studies is detailed. They are both from the Moroccan economic infrastructure. Besides, each one of them is about a different interdependency in a completely different coalition of enterprises. The information concerning all the metrics is collected using a survey distributed to

the four institutions.

Four institutions are chosen to conduct our study, with IT6 and ONEE belonging to a SoS and AIC and the anonymous automotive company belonging to another one.

- **IT6:** a consulting firm specializing in strategy, organization and corporate governance. Located in Rabat.
- **ONEE (Office National de l'lectricit et de l'Eau potable):** a pillar of the energy strategy and the state's arm in the water and sanitation sector in Morocco. Located in Casablanca.
- **AIC (Ateliers Industriels Chrifiens):** a firm specializing in the production of advertising signs, road signs, road safety devices, street furniture, etc. Located in Kenitra.
- **Anonymous automotive company located in Kenitra.**

Every enterprises' coalition is considered as a SoS, where enterprises are represented by CS and interdependencies represent the collaborations between enterprises.

It is worth noting that information has been collected about the institutions' functioning in addition to the disturbances and barriers hindering the interdependencies between them. This also helped to calculate the exchange inefficiency.

Information regarding the firms/office and their collaborations with other institutions could not be disclosed, because they contained confidential commercial information. However, tables will be presented in order to identify interoperability barriers and unveil details about their nature through interoperability levels.

In the remaining part of this section, the first case study's application results (IT6 and ONEE) will be discussed, followed by the second case study (AIC and the anonymous automotive company).

3.5.1 First Case Study

Based on the collected information, the matrices represented in Table 3.5, Table 3.6, Table 3.7 and Table 3.8 reveal details about the nature of the barriers identified through all interoperability levels (business, process, service and data) at the time when IT6 enterprise and ONEE started to interact.

	Human	Legislation	Finance	Decision making	Commercial approach	Culture of enterprise
Business	0	0	0	1	1	1
Process	1	0	0	1	1	1
Service	1	1	1	1	0	0
Data	1	0	0	1	1	1

Table 3.5:: Organizational matrix of the interdependency between IT6 and ONEE.

	Procedure	Norms and standards	Method of work	Technological
Business	1	1	1	1
Process	0	1	1	1
Service	0	1	0	0
Data	1	0	1	1

Table 3.6:: Functional matrix of the interdependency between IT6 and ONEE.

	Logical	Physical
Business	1	0
Process	0	0
Service	0	0
Data	1	1

Table 3.7:: Technical matrix of the interdependency between IT6 and ONEE.

	Geographical barriers
Business	0
Process	0
Service	0
Data	1

Table 3.8:: Geographical vector of the interdependency between IT6 and ONEE.

According to the defined method of barriers evaluation, the obtained degree of global barriers (DB) is 0.45313 (45.313 %). While the obtained exchange inefficiency (EI) of the interdependency in question is 0.3333 (33.33 %). Consequently, the obtained structural operability indicator's (SOI) value is 0.61136. Therefore, the structural operability rate is equal to 61.136 %.

Information is extracted from the same survey in order to fill in the table proposed

in Lane and Valerdi (2011). The initial matrix proposed in Lane and Valerdi (2011) consists of a combination of three categories of barriers: organizational, conceptual and technical barriers through the levels of interoperability in terms of business, process, service and data. Table 3.9 provides the application results of the method. The idea behind these applications is to cross-compare the results of both approaches.

	Syntactic	Semantic	Authorities	Organization	Platform	Communication
Business	1	1	0	1	1	1
Process	1	1	1	0	1	0
Service	1	1	1	0	0	0
Data	0	0	1	1	1	1

Table 3.9:: Results of the application of the approach in Lane and Valerdi (2011) to the interdependency between IT6 and ONEE.

As a result, the obtained degree of global barriers is 0.66667 (66.667 %). Since the inefficiency of exchange rate stays the same, the obtained value of SOI is 0.52859. Therefore, the structural operability rate is equal to 52.869 %.

3.5.2 Second Case Study

The second case study concerns an industrial enterprise: AIC (Ateliers Industriels Chrifiens), specialized in the production of road signs, motorways, safety devices, traffic management and access control.

60% of AIC's clients are public institutions represented by the Ministry of Equipment and Transportation and 40% of its clients are state-owned companies. As in the first case study, the inefficiency of the exchanges and the barriers identified are investigated during the interoperation of AIC with one of its partners, an anonymous automotive company, through a questionnaire. The survey aims to deduct the way the company functions, to overcome the different natures of the obstacles and barriers as well as to calculate the inefficiency of the exchanges while interoperating.

Based on the survey, the matrices represented in Table 3.10, Table 3.11, Table 3.12 and Table 3.13 reveal details about the nature of the barriers identified through all interoperability levels (business, process, service and data) at the time when AIC and the anonymous company established the interdependency.

According to the defined method of barriers evaluation, the obtained degree of global barriers (DB) is 0.04687 (4.687 %). While the obtained exchange inefficiency (EI) of the interdependency in question is 0.1333 (13.33 %). Consequently,

	Human	Legislation	Finance	Decision making	Commercial approach	Culture of enterprise
Business	0	0	0	0	0	0
Process	0	0	0	0	0	0
Service	0	0	1	0	0	0
Data	0	0	0	1	0	1

Table 3.10:: Organizational matrix of the interdependency between AIC and the anonymous company.

	Procedure	Norms and standards	Method of work	Technological
Business	0	0	0	0
Process	1	0	0	0
Service	0	0	0	0
Data	0	0	0	0

Table 3.11:: Functional matrix of the interdependency between AIC and the anonymous company.

	Logical	Physical
Business	0	0
Process	0	0
Service	0	0
Data	0	0

Table 3.12:: Technical matrix of the interdependency between AIC and the anonymous company.

	Geographical barriers
Business	0
Process	0
Service	0
Data	0

Table 3.13:: Geographical vector of the interdependency between AIC and the anonymous company.

the obtained structural operability indicator's (SOI) value is 0.92094. Therefore, the structural operability rate is equal to 92.094 %.

As for the first application, Table 3.14 illustrates the application results of the approach proposed in Lane and Valerdi (2011).

	Syntactic	Semantic	Authorities	Organization	Platform	Communication
Business	0	0	0	0	0	0
Process	0	0	0	1	0	0
Service	0	0	0	1	0	0
Data	0	0	0	1	0	0

Table 3.14:: Results of the application of the approach in Lane and Valerdi (2011) to the interdependency between AIC and the anonymous company.

As a result, the obtained degree of global barriers is 0.125 (12.5 %). Since the inefficiency of exchange rate stays the same, the obtained value of SOI is 0.8709. Therefore, the structural operability rate is equal to 87.09 %.

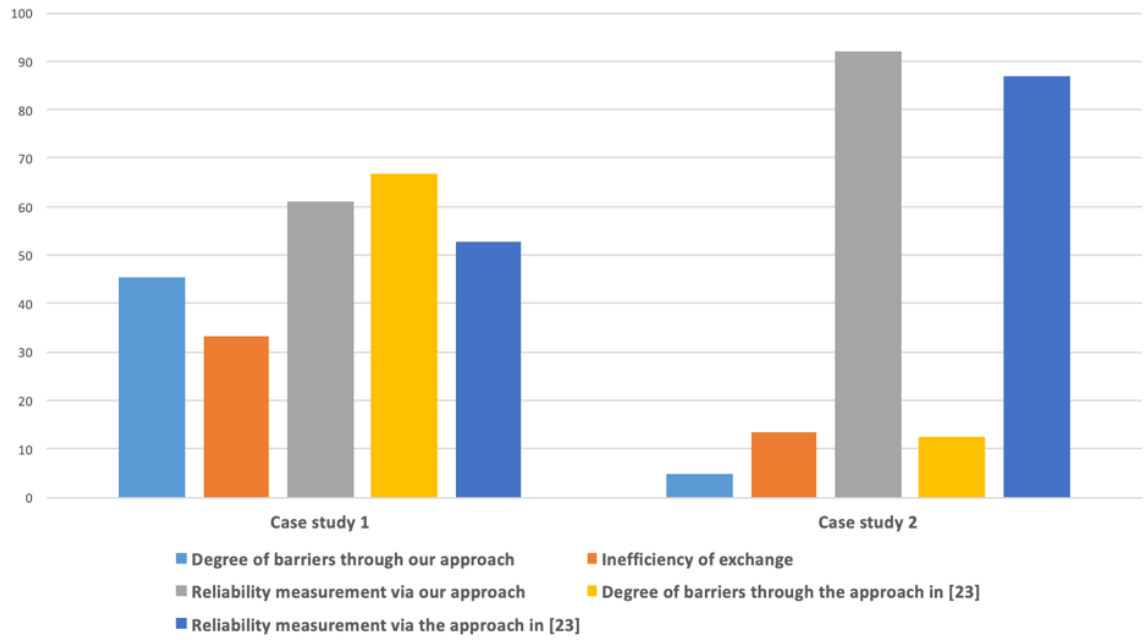

Figure 3.2: Calculation results illustration.

Figure 3.2 illustrates an intelligible view through all results. The results obtained by the calculations done to both case studies demonstrate that the results of our approach are inherent to those obtained by the application of the approach in Lane and Valerdi (2011). This is logical, as the proposed interoperability matrices are inspired by the same reference.

Regarding the obtained results, the reduction of the barriers implies the increase

of the SOI values. This means that a lack of identification of interoperability barriers through the previously presented levels may lead to a miscalculation and to wrong evaluation of structural operability.

In the first case study, the comparison between the rates of barriers revealed that the poor estimation of barriers affects the rate of barriers. Therefore, it is necessary to reduce the obtained rate of interoperability barriers (66.667%) and get a barrier ratio closer to reality (45.313%), this requires a well-conducted study and a deep analysis of the barriers that actually affect interoperability.

In other words, it is necessary to identify the maximum of barriers for each category and to verify the existence of other potential categories of barriers for the studied case in order to evaluate SoS structural operability in the most reliable manner through the proposed approach.

3.6 Modeling and Implementation

This section's objective is to model the presented approaches using Unified Modeling Language (UML) for an eventual implementation and automatization. UML is a widely used language in the software engineering field. It provides a standard visualization of the system's conception.

The visualization of the system's conception is offered through a set of diagrams. It includes activities, the system's components, the interactions, the system's behaviors and external interfaces.

The diagrams, as a partial graphic illustration of the system's model, need to cover the model (preferably in a complete manner). Correspondingly, UML diagrams are classified into different classes. They represent two different views of the system:

- **The structural diagrams:** they provide a representation of the system's static structure. This is done using objects, attributes operations and relationships. This class includes class diagram, package diagram, object diagram, component diagram, composite structure diagram and deployment diagram.
- **The behavioral diagrams:** they provide a representation of the behavior of the system. This is done by presenting interactions between the system's objects and the internal states changes. This class includes activity diagram, sequence diagram, use case diagram, state diagram, communication diagram, interaction overview diagram, timing diagram.

3.6.1 Use Case Diagram

The cornerstone of any system is the functional requirements that the system fulfills. Use case diagrams are used to analyze these high-level requirements. Each use case represents what the system is able to provide.

Figure 3.3 represents the use case diagram of the interoperability assessment module. This completes the approaches for resilience and risk assessment, detailed in the coming chapters. The SoS administrator, that executes the proposed process of interoperability assessment, can perform numerous actions. The first preliminary action, the user can do, is to choose whether the process will be applied on a simulated scenario or a stored scenario.

In the first case, the creation of the interdependency that will be subject to the process execution is preceded by the creation of the CS engendering it. The user should enter all the information necessary to the creation of two CS. Then, the creation of the interdependency comes with the designation of the workflow pathways through the creation of interdependencies.

On the other hand, if the SoS administrator loads a pre-stored interdependence, he will need to load the SoS including it first. Then, he can choose, which interdependency will be concerned by the calculation.

The first indicator that the user can calculate is the exchange inefficiency. It represents the arithmetic mean of the overall rates of irregularities in exchange within the SoS. These irregularities are represented by the arithmetic mean of "the three Fs": failure rate of exchange, failure of interpretation and flouting.

As mentioned earlier, the failure rate of exchange represents the rate of unsuccessful exchanges between CS. Accordingly, the exchanges here refer to data, information, documents, etc. exchanged through an interdependency between at least two CS, two capabilities or a CS and a capability.

The failure of interpretation represents the rate of unsuccessfully interpreted exchanges between CS. It is calculated by devising the number of unsuccessfully interpreted information by the total number of exchanges.

The flouting represents the rate of nonconforming information, data, document or anything generated by a CS and transferred to another. It is calculated by devising the number of nonconforming information upon the number of the total information received.

Another action the system can perform is the calculation of the degree of bar-

riers. It evaluates the obstacles hindering an interaction between CS through interdependencies. The barriers are classified into four classes: organizational, functional, geographical and technical barriers.

Organizational barriers represent the structural arrangement of the CS within SoS. Functional barriers define the statement of need between two CS planning to exchange data, information, documents, etc. Technical barriers represent the rules and criteria that govern the implementation of the system aspect and support interactions amid the SoS. Geographical barriers represent the geographical context that embraces the implementation of the SoS.

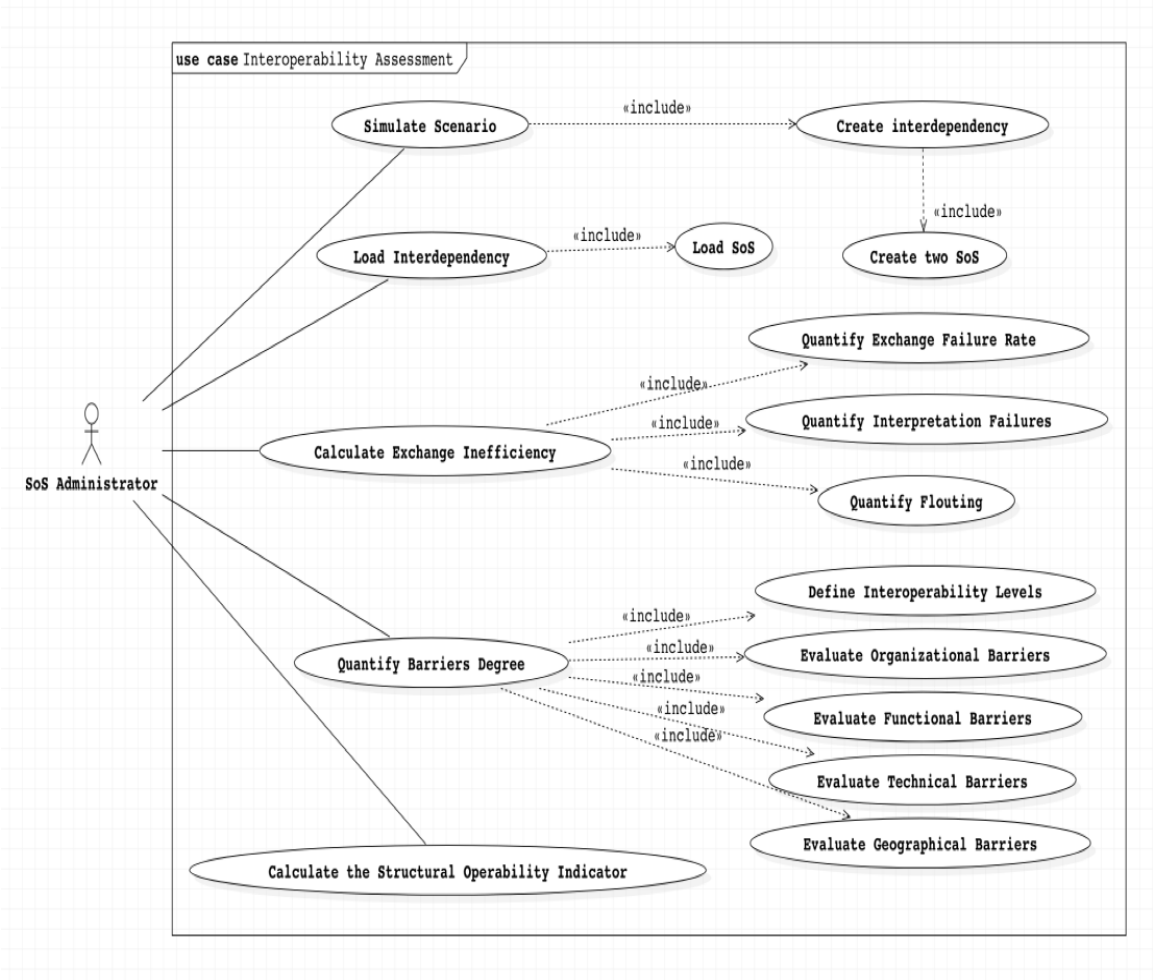

Figure 3.3: Use case diagram of the interoperability assessment module.

Furthermore, they are evaluated with regards to interoperability levels, which are: business, process, service and data. These levels are useful in the evaluation of the severity of barriers that threaten the interdependencies relating CS. Finally, the

ultimate barriers degree is calculated by the arithmetic mean of all the values of the other classes.

Another action the user can perform is the calculation of the structural operability of an interdependency. It is an important indicator to SoS structural assessment. It is the calculation result of the degree of barriers and the exchange inefficiency arithmetic average.

The return is the rate of the operability of a coalition of interdependent CS by considering its exposition to the threats which are approached as barriers in addition to the exchange inefficiency.

3.6.2 Activity Diagram

Activity diagrams are extremely important to the modeling process. It is useful for an effective description of all the actions and activities within the system, in addition to the flow linking them, that can be sequential or in parallel.

Figure 3.4 illustrates the process of the interoperability assessment. It begins by selecting the interdependency to analyze. This is done by choosing the CS embracing the interdependency. Then, the evaluation process is launched.

The evaluation of barriers through interoperability levels provides the degree of all barriers. Moreover, the evaluation of the three Fs provides the other values that contribute to the calculation of the structural operability.

Eventually, these indicators contribute to the calculation of the structural operability indicator. This reflects the degree of the structural resilience of the interdependency with regards to the existing or potential obstacles.

3.7 Conclusions

Eventually, interoperability is a quality and not a characteristic of a system, and it must be defined for at least a pair of systems by decision-makers in the conceptual design phase. In addition, it can be considered as a metric dedicated to the structural evaluation Han et al. (2012). It helps to diagnose the interdependencies forming the basic SoS structure.

In SoS literature, interoperability is a newly emerging field of study, thus, its literature still spalled. However, it is extremely important to assess the interoperability

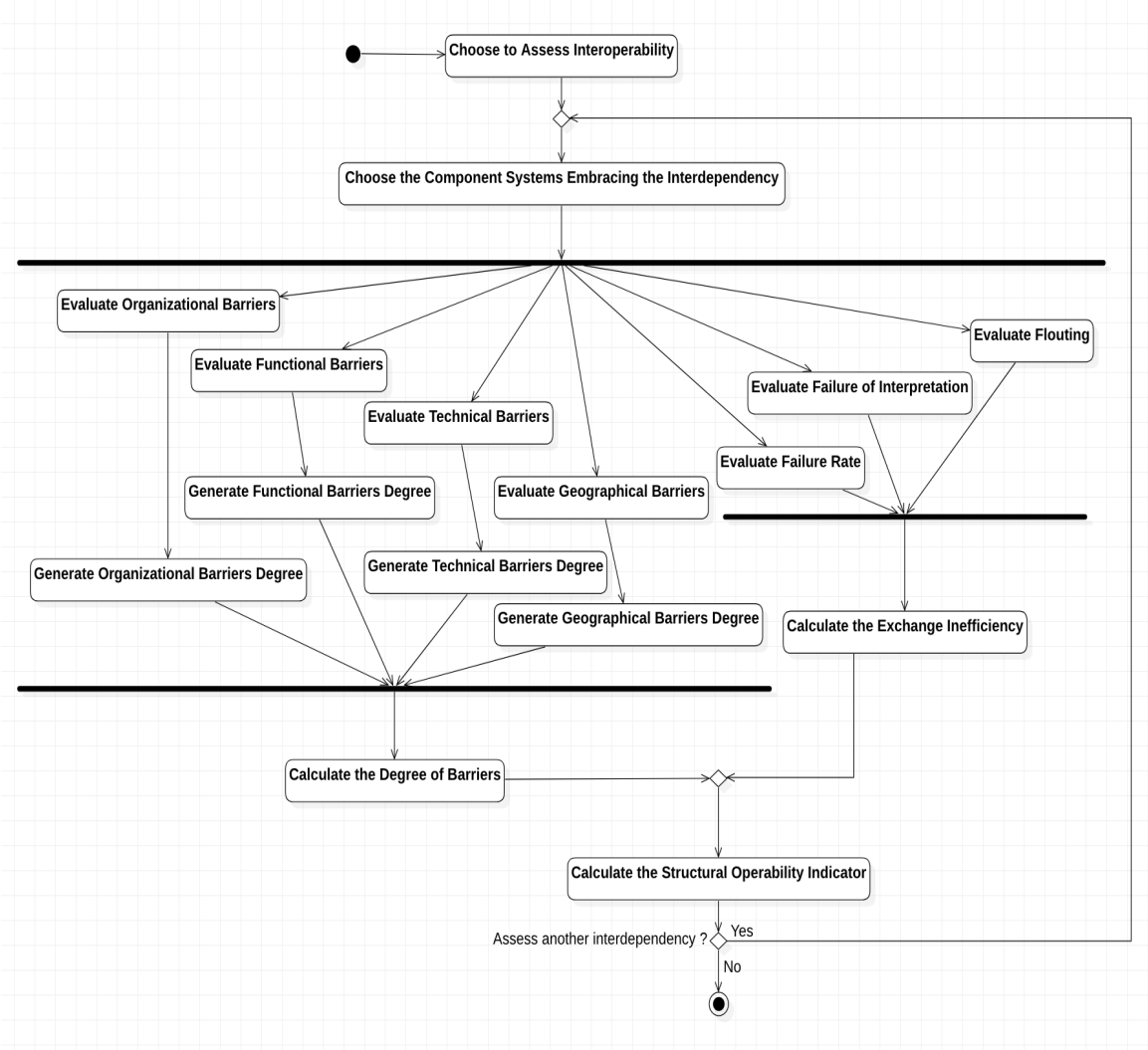

Figure 3.4: Activity diagram of the interoperability assessment module.

of CS forming the global SoS for eventual structural resilience assessment.

In addition, interoperability is a quality that can be viewed from various perspectives. Consequently, an illustrative classification of interoperability axes is detailed. It represents the adopted perspective to handle interoperability. It embraces barriers, scopes and levels.

In this chapter, an approach dedicated to SoS structural operability assessment is detailed. The aim is to analyze the SoS structural resilience through interoperability assessment with consideration to the dynamic of the structure. This aspect is strongly related to a special characteristic of SoS, it is called extensibility. It is due to continuous evolvement and change of SoS structure.

A set of indicators is included in this approach. They are based on interoperability and exchange inefficiency assessments. The idea is to analyze and evaluate the structural operability of the existing interdependencies, with interdependencies representing links between CS within the SoS.

The motivation behind such a methodology is to inspect the structure of SoS, especially the interdependencies between CS in order to evaluate, assess quantify and even anticipate the SoS operability level.

This chapter also presents the application of the theory to two different case studies in addition to a comparison of the different obtained results. A prototype, designed using UML, is also embraced in this chapter. It provides a standard visualization of the system's conception for eventual SoS structural resilience assessment.

The visualization of the system's conception is offered through two diagrams:

- *The use case diagram:* in order to analyze these system's high-level requirements, and to present the actions the system can provide.
- *The activity diagram:* to describe all the action and activities within the system, in addition to the flow linking them.

Chapter 4

SoS Resilience Assessment trough Risk and Structural Analysis

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4.1 Introduction

Nowadays, we expect of SoS more than just to be functional, but also to be reliable, to preserve their performance, to complete the required functions and most importantly to anticipate potential defects.

The relationship with resilience is among the numerous perspectives tackling reliability in the context of SoS. It is about the consequences in case of disturbances and associated uncertainties. Resilience is defined as the ability of systems to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time, composite costs and risks Aven (2011), Uday and Marais (2014), Tran et al. (2016b), Norris et al. (2008).

As previously mentioned, resilience is about the consequences in the case of disturbances and associated uncertainties, and it reflects the ability of the system to withstand them and recover Aven (2011), Sherrieb et al. (2010). A system is resilient if it can face disturbances and gets back to normal performance within an acceptable duration Aven (2011), Uday and Marais (2014), Tran et al. (2016b), Norris et al. (2008).

In this chapter, two complementary approaches are proposed in order to analyze SoS structure in an attempt to contribute to structural resilience assessment and risks impact forecast. It starts with a detailed classification of SoS risks based on their natures and sources. Next, a risks' monitoring approach is explained, it is conceived to evaluate, analyze and supervise risks which represent the catalyzers of destabilizations. Then, that design is supported by a second approach to weigh up the failure impact of each CS on the SoS performance and process continuity. The combination of these approaches helps to have a futurist perspective towards the potential risks threatening the SoS, their impacts and CS' failures influence on the SoS overall performance and process continuity.

The idea behind the adopted perspective to handle SoS resilience is simple: to be able to measure each CS failure impact on the rest of the global system and working process. This helps to be cognizant of the rate of the system's survivability after each CS failure.

The remaining part of this chapter is structured as follows:

- Section 2 details the proposed approach dedicated to risks assessment.
- Section 3 explains the complementary approach dedicated to structural analysis.
- Section 4 details the inherent structural resilience constraints.

- Section 5 presents a model of the presented approach using UML.
- The last section summarizes the work and draws conclusions.

4.2 Risk Management

An interdisciplinary discussion has developed. It concerns how engineers and researchers can incorporate risk assessment into the engineering of complex systems, in general, and, especially, in SoS and critical infrastructures.

This section gives a brief overview of prominent risks assessment works. Multitudinous works and publications attempt to lead the effort behind shedding more light on risk assessment and its relationship with resilience and reliability.

Much of the work focusing on risk assessment has been about proposing definitions and literature reviews. They appear within various scientific fields and are often tailored to specific applications of interest. As in Medal et al. (2011), authors propose a review where they discuss articles from the literature, place them into categories, and suggest topics for future research. In Coles et al. (2011), authors proposed a definition of resilience measures using elements of a traditional risk assessment framework to help clarify the concept of resilience and as a way to provide risk information. This work presets diverse convergences between resilience quantification and risk assessment based on the concept of loss of service.

In Lever and Kifayat (2016), a survey of significant risks' elements which impede these large complex collaborative infrastructures. Authors expanded the perception of risk via an in-depth review of the associated literature. They also intend to monitor risk and quantify risks in addition to the visualization of interdependencies associated with the components forming the SoS and outline the severity of potential consequences.

A holistic criticality assessment methodology suitable for the development of an infrastructure protection plan in a multi-sector or national level is detailed in Theoharidou et al. (2010). The authors aim to integrate existing security plans and risk assessments performed in isolated infrastructures in order to assess security risks. They define three different layers of security assessments with different requirements and goals (the operator layer, the sector layer and the intra-sector or national layer). They determine the characteristics of each layer, as well as their interdependencies. The methodology focuses on addressing the issue of interdependency between infrastructures and on the assessment of impact and risk transfer.

Considering discussions of risk assessment from a variety of communities, the common aspect of all these definitions is that it is defined as unexpected or unforeseen changes and disturbances that may put the system in jeopardy. However, what is extremely important and lacks in literature is the risks impact forecast, especially in SoS context. This was the main motivation to start this work, as an attempt to answer to this demand.

The work presented in this chapter aims to tackle the anticipation of risks menacing SoS stability. This is done through two complementary approaches: one dedicated to risks monitoring and the other to structural analysis.

The risks management approach is based on two important steps:

- Risks classification
- Risks monitoring

The proposed approach aims to address and manage risks menacing SoS stability. This section proposes a classification of risks in addition to a risk monitoring design for anticipatory and preventive reasons.

4.2.1 Risk Model

As SoS has a special architecture with special properties as distribution, heterogeneity, complexity, etc. it is crucial to inspect the potential risks sources that could disturb the operational and functional return of SoS.

There is a consideration of any barrier that could continuously or in an intermittent manner discommode, interrupt or put an end to an interaction between two (or more) CS as a risk. In Figure 4.1, SoS risks are classified based on their natures and sources. Here are the main risks classes:

- Vulnerabilities,
- Obstacles,
- Emergences.

Vulnerabilities represent the weaknesses of the system that can be the subject of possible exploitation and consequently put the system at risk. They also can be classified into two categories:

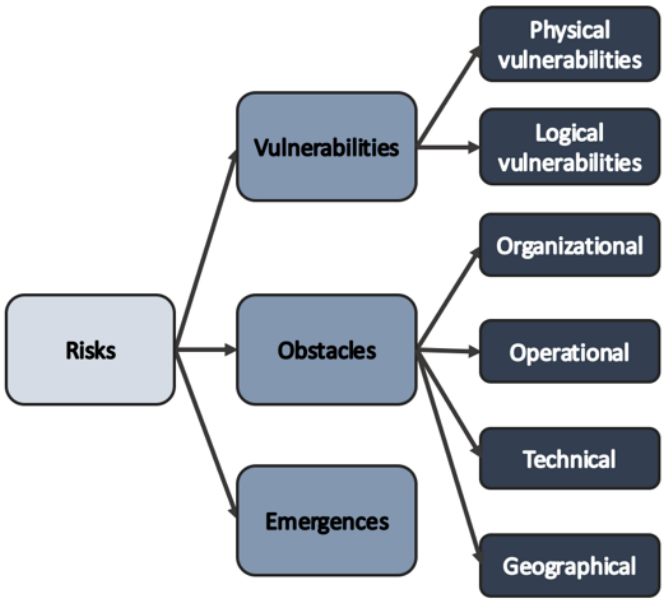

Figure 4.1: Risk's classification.

- **Physical vulnerabilities:** linked to the physical basis of the system's structure, i.e. the entities, the used links, machines and server rooms. Unauthorized access of a malicious person to the infrastructure may lead to titanic problems.

- **Logical vulnerabilities:** related to the software, applications, protocols or procedures that can be exploited by a malicious activity may put the SoS at huge risks.

While obstacles represent the barriers that could possibly disturb, interrupt or intercept the interdependencies between interacting CS. A taxonomy of obstacles is proposed. It will be adopted in the proposed approach. Here are the four classes and their definitions:

- **Organizational obstacles:** they concern human, legislative, decisional, financial obstacles, commercial approaches and cultures that can discommode the interactions between CS.

- **Functional obstacles:** they are related to the incompatibility of procedures, norms and standards to present and communicate information, as well as the methods of work and technical incompatibilities that may perturb the interactions between communicating CS.

- **Technical obstacles:** they are related to the technical support of interactions. They are classified into two levels: logical and physical. Logical is about the obstacles related to exploited software, programs, etc. and physical is related to the physical structure supporting the logical solutions.

- **Geographical obstacles:** they represent anything that blocks the pathway between two CS, this can be any natural feature such as mountains or even natural disasters that prevent the interaction from being successful.

Finally, emergence represents a principle in classical systems theory, that generally suggests that global system properties (patterns, capabilities, structure and behaviors) may be developed from the interaction of CS Hitchins (2003). Emergences may represent prominent risks to the SoS if they affect its performance.

Other definitions are proposed to sire the concept of emergence. In Ryan (2006), emergent behavior is defined as what cannot be expected through analysis. While in Norman and Kuras (2006), emergent behaviors refer to the properties arising from cumulative interactions between CS within the SoS.

In complex systems, this notion generally includes the following commonly held points Jamshidi (2008a):

- Emergent properties exist only at the system level.

- Emergent properties are not held by any of the isolated elements.

- Emergent properties are irreducible. They simply cannot be understood, explained, or inferred from the structure or behavior of constituent elements or their local properties.

- Understanding the cause-effect relationships can only be established through retrospective interpretation. This renders traditional reduction-based analytic techniques are incapable of give useful predictions of emergent system-level behavior.

Figure 4.1 summarizes the detailed classification of risks. To effectively deal with them, an appreciation of the philosophical, methodological and axiomatic underpinnings is required. The non-governance of the disorder at the very beginning can complicate the restoring of CS' performance after an incident.

4.2.2 Risk Monitoring

The use of the dashboard is an attempt to illustrate, preferably in real-time, qualitative indicators related to risks striking the SoS at a given time and in a geographic location or how it could possibly affect it in the future. The dashboard could be used for both anticipative and preventive reasons. For optimal exploitation of the dashboard and effective anticipation, it is more advisable to apply it, similarly, on every single interdependency and try to anticipate as many scenarios as possible.

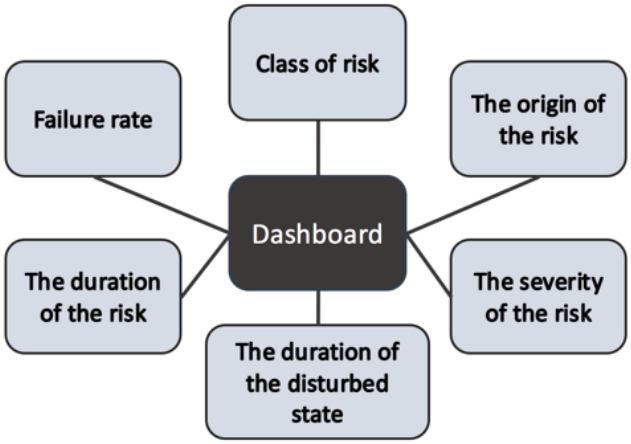

Figure 4.2: Dashboard for risks' supervision.

It is worth noting that the elements included in the dashboard, shown in Figure 4.2, are not exhaustive. They are called control points, as they are used to determine different risk characteristics and implicitly the SoS state.

The examined control points may change according to the studied SoS. The idea behind the proposition of the dashboard is not to propose a standard for SoS monitoring but to emphasize the importance of monitoring in such context and suggest an outline of essential features.

Let us examine the key elements included in the dashboard in order to understand their use:

- **The origin of risk:** in order to correctly address a risk, it is crucial to know its origin, which also reflects its nature. Besides, knowing where a risk came from helps to understand the risk itself and to elaborate pertinent countermeasures. In fact, there are numerous sources of risks, it could be environmental, human, technical, etc. Accordingly, a risk may be intentional i.e. it could be organized, managed and targeting a vulnerability in the SoS, in this case, the origin may

be internal (e.g. coming from CS) or external (e.g. as a consequence of an environmental disaster). Or it could be unintentional e.g. as in the case of environmental risk or a human intervention that led accidentally to a problem.

- **The severity of the risk:** it is very important to know how much the SoS performance has degraded. For this reason, a classification of degrees of nuisance is proposed according to the degree of the SoS disturbance:

  - It is called 1st degree if it is quick and does not disturb the performance of the SoS.

  - It is called 2nd degree if it remains weak but affects slightly the performance of the SoS for a short period of time before it returns to its initial state.

  - It is called 3rd degree if it is able to significantly disrupt the performance of the SoS.

  - It is referred to as a 4th degree if it may provoke an interruption to the SoS performance and it becomes difficult for it to return to its initial state.

  - It is called 5th degree if it can cause a breakdown of the system which makes it impossible for the SoS to regain its initial state

- **The duration of the risk:** represents the duration that took (or may take) a system to resist the risk. As the risk may be instant or slow, the resistance duration also changes according to the risk's duration. This has no relation to the degree of severity of the risk.

- **The duration of the disturbed state:** represents the period where the system leaves its initial state (this depends on the degree of the risk and its duration). In some cases, it may be significantly greater than the duration of the risk, and this may be due to several factors including the degree of risk and the criticality of the systems amid the SoS undergoing this risk. The notion of criticality will be discussed further in this paper.

- **The failure rate:** represents the rate of CS that failed to return to their initial states after the occurrence of the risk.

$$FR(\%) = \frac{NumberofFailedCS}{NumberofCS} \times 100 \tag{4.1}$$

- **Risk's type:** refers to the class of the risk according to the risk model in the third section.

A major reason why risks may occur and may have predominant consequences is the existence of vulnerabilities. They have existed since the system was implemented. Some of them can be planned from the design stage to be corrected before the system is built, others can be unpredictable and become identifiable only after the SoS has been set up. This triggers the need for frequent maintenance of the system's infrastructure, entities, links, programs and software in order to fix them.

But, why do we need to monitor risks?

First, there are preventive reasons as it is important for engineers and management authorities to have an anticipative and futurist perspective to the SoS behavior, interdependencies' states and overall performance. This helps them to be prepared for eventual risks.

The second reason behind monitoring is real-time supervision and protection of the SoS. The proposed approach helps to get the real-time state of the performance of the system. In case of a problem, the supervision authority is notified right away. Therefore, some countermeasures to be considered.

The general idea behind the use of a risks monitor is to reduce the response time of the SoS to face risks as the earlier the problem is identified the more it is handled efficiently and its consequences can be limited.

4.3 Structural Analysis

SoS can have a topology that is inherent to its static representation of its components and the workflow and interactions pathways Filippini and Silva (2014). It is a useful tool to model and assess large-scale, diverse and changing tasks and missions that may be formed and organized dynamically so as to achieve a set of targets.

The idea is to create an interdependency network representing the SoS topology with focus on exchanges pathways. The interdependency network is the overall representation of all the relevant functional interdependencies. It is sector neutral, most importantly the CS do not necessarily have to share the same physical domain. Therefore, the interdependency is the reference model for the structural analysis.

Structural analysis leads to the evaluation of numerous indicators. It starts with CS related indicators, such as: criticality, frailty, failure impact susceptibility, direct and impacts. And it finishes with a global SoS indicator baptized structural resilience.

This gives an idea about the dependability of the global system on each CS, the

influence of each CS on the SoS, and finally, the latter's resilience level. The CS related indicators' calculations should be done, similarly, to every single CS based on the SoS structure.

It is important to note that criticality and frailty calculations represent a cross-road in the structural analysis process. In case of a distributed SoS into regions, there is an extension of calculations through failure impact and susceptibility indicators. If it is not distributed the measurements extend to include direct impacts calculation, direct impact matrix, permanent and structural resilience calculation. See Figure 4.3.

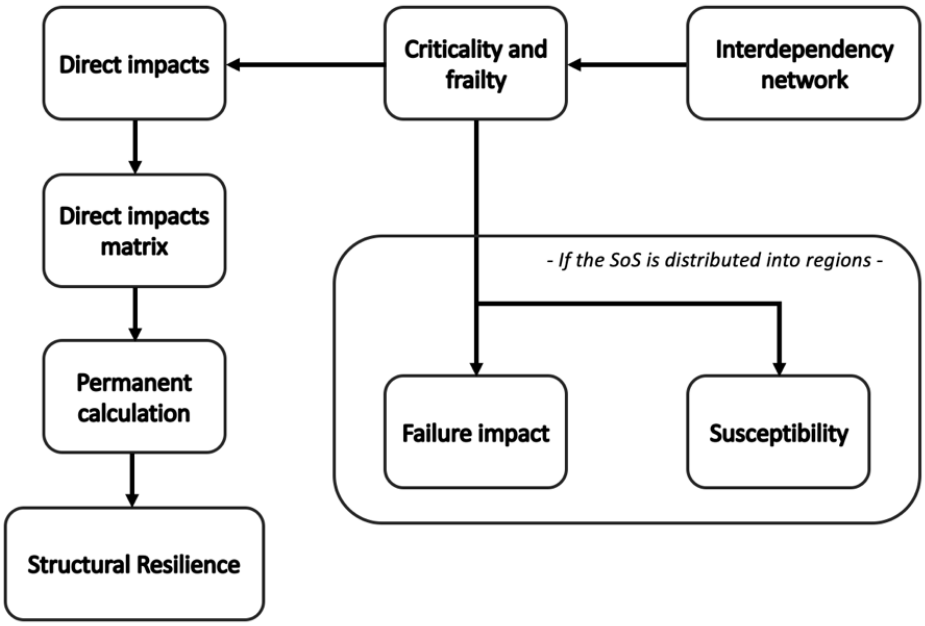

Figure 4.3: The structural analysis process.

With this in mind, failures represent the abortion, suspension or alteration of an operation activity between at least two CS. They are caused by risks' occurrence.

While process continuity refers to the resumption of the system's performance, groups and the global SoS after the occurrence of the disturbance. The correlation between the concept of process continuity and the metrics detailed in this chapter is that the anticipation of the impact of a failure, based on structural analysis, can help to foresee its impact on the performance on SoS and the process continuity after recovery.

4.3.1 Interdependency Network

Interdependencies are concerned by the ability of CS to share, exchange and correctly interpret information, material and even energy sometimes, so as to achieve the common target with respect to some rules of interactions Billaud et al. (2015), DeLaurentis (2005).

The idea behind interdependency analysis is to focus on workflow pathways and directions, as it is illustrated by black arrows in Figure 5. The analysis of interdependencies' set emphasizes the functional interdependencies relevance. In addition, it identifies clearly the process sequencing by representing functional services to be acquired by CS and interdependencies between them or between the capabilities by links.

A SoS can be given a topology that accounts for the static representation of its components and the manner they interact and cooperate Ed-daoui et al. (2017b), Ed-daoui et al. (2016a), Ed-daoui et al. (2018c), Filippini and Silva (2014). The idea is to focus on the component's interface, where data, services and quantities are exchanged through functional relationships, i.e. functional interdependencies.

It is important to evaluate the effect of topology and possible systems' performance degradation on the SoS as it helps us implicitly to evaluate its resilience and capability to face partial failures and CS' loss of operability.

Correspondingly, CS have the responsibility to determine their interdependencies as it is propitious to systems self-directed autonomy. Accordingly, it is mandatory to be directed by the achievement of the SoS's final mission. Interdependencies are also a practical solution, since they provide the possibility to track the workflow, traffic and processes directions.

In fact, the interdependency network analysis technique has been applied first to operational networks based on the functional dependency network analysis (FDNA) Guariniello and DeLaurentis (2013). This method is used to evaluate the effect of topology and possible degraded functioning of one or more systems on the operability of each system in the network. Therefore, the resilience of SoS can be evaluated in terms of capability to reduce the loss of operability when CS are affected by partial failures.

4.3.2 Criticality and Frailty Analysis

Criticality and frailty are two structural properties that assess the system through the interdependencies network. A CS is influenced by upstream CS and it influences the downstream CS with regard to the workflow pathway.

In Ed-daoui et al. (2019a) and Ed-daoui et al. (2018c), frailty (or vulnerability, as it is called in the cited reference. The word vulnerability is not used here as it is exploited to express a class of risks) and criticality sets are presented as structural properties that can be analyzed in the interdependency network. A CS is affected by the ones on which it depends on and it is critical to the ones depending on it. The interdependency is related to the workflow pathway between CS.

Figure 4.4 represents a simple example of three CS. The idea is to locate frailty and criticality sets for CS '2' with regards to the workflow pathway. CS '2' is critical to CS '3' and frail to CS '1' at the same time. This depicts the difference between frailty and criticality and their positions towards the SoS workflow pathway.

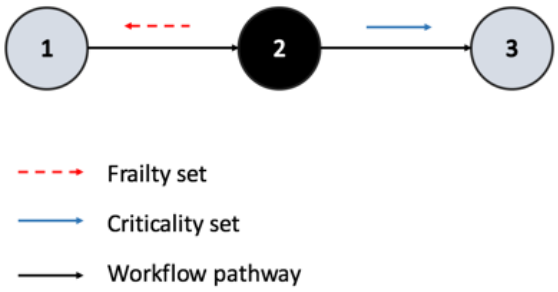

Figure 4.4: Frailty and criticality positions towards workflow pathway.

The criticality represents how much the process continuity of the SoS is affected by each CS while the frailty represents how much the process continuity of the SoS influences each CS. This illustrates the difference between frailty and criticality and their positions towards the workflow pathway.

Practically, the criticality of a CS is the division's result of the CS number that are directly or indirectly affected by the system in question number by the total number of CS in that region. See formula 4.2.

On the other hand, the frailty of a CS is the division's result of the CS number that influence directly or indirectly the CS in question by the number of CS in that

region. See formula 4.3.

$$(\forall n_i \in G_j) : Criticality(n_i) = \frac{Card(C(n_i))}{Card(G_j)} \tag{4.2}$$

With:
$i, j \in \mathbb{N}$
$Card(C(n_i))$: the number of CS forming the group embracing the CS n_i.
$Card(C(G_i))$: represents the number of CS that are directly or indirectly affected by the failure of the system . The CS should be in the same group as n_i.

$$(\forall n_i \in G_j) : Frailty(n_i) = \frac{Card(F(n_i))}{Card(G_j)} \tag{4.3}$$

With:
$i, j \in \mathbb{N}$
$Card(C(n_i))$: the number of CS forming the group embracing the CS n_i.
$Card(C(G_i))$: represents the number of CS that affect directly or indirectly n_i by their failures.

At this stage, the SoS' groups are supposed to be represented by the set $\{G_1, G_2, ...\}$. Moreover, frailty metric values range goes from 0 for not frail at all to 1 for extremely frail. The frailty value may be multiplied by 100 in order to get the criticality rate.

4.3.3 Failure Impact and Susceptibility Calculations

Failure impact is a structural metric conceived to measure each CS failure impact on the rest of systems and SoS viability with consideration to the repartition of the SoS into groups. The failure impact value of a system is obtained by multiplying its criticality value (with correspondence to its position towards the process inside the containing group) by the same group's criticality value (corresponding to the process inside the SoS). As it is shown in formula 4.4.

$$\forall (n_i, g_j) \in G \times F : FI(n_{ij}) = Criticality_{System}(n_i) \times Criticality_{Group}(G_j) \tag{4.4}$$

With:
$i, j \in \mathbb{N}$

$Criticality_{System}$ values range goes from 0 for not critical at all to 1 for extremely critical. $Criticality_{Group}$ is equal to 1 in case there is no interdependency between groups.

Furthermore, groups criticality values are calculated following the same tactic that has been adopted to calculate each CS criticality on the rest of CS within the same group, with consideration of itself. This means that in addition to the groups following the same workflow pathway, the group in question joins the group's criticality set.

The failure impact metric takes into account all variables taking part in the system's forming. If a system has a high failure impact that means that an important part of the SoS could be affected in case of its deficiency. This means that the infrastructure is not resilient and robust enough to overcome its failure.

Contrarily to the failure impact metric, susceptibility is a metric that evaluates CS fragility to the process continuity, with consideration to the repartition of the SoS in question into groups.

The susceptibility of a CS inside a SoS is obtained by the multiplication of its frailty (with correspondence to its position towards the process inside the containing group) by the frailty value of the same group (corresponding to the process inside the SoS). As it is shown in formula 4.5.

$$\forall(n_i, g_j) \in G \times F : S(n_{ij}) = Frailty_{System}(n_i) \times Frailty_{Group}(G_j) \tag{4.5}$$

With:
$i, j \in \mathbb{N}$

$Frailty_{System}$ values range goes from 0 for not frail at all, which means that the CS is independent inside its group and does not receive any workflow from any CS, to 1 for extremely frail, which means that the CS receives flaw from all CS inside the same group. $Frailty_{Group}$ is equal to 1 in case there is no interdependency between groups.

Correspondingly, the calculation of the frailty of each group on the rest of groups within the SoS is done following the same tactic that has been adopted to calculate the criticality of each group on the rest of groups within the same SoS, with consideration of itself. This means that in addition to the groups following the same workflow pathway, the group in question joins the group's frailty set.

Failure impact and susceptibility metrics are both structural metrics dedicated to the evaluation of a SoS interdependence on each one of its CS and vice versa. This implies the evaluation of SoS resilience and capability to overcome disturbances.

4.3.4 Direct Impacts Calculations

The direct impact metric is conceived in order to be able to measure the direct impact of every CS on every other CS forming the SoS. It is a more specific and precise metric compared to the previously mentioned ones.

Practically, it is calculated using the criticality and frailty measures of the CS intended to assess their impact. Formula 4.6 illustrates the expression to calculate the impact of the CS 'x' on the CS 'y'.

It is worth noting that both CS belong to the same SoS. Besides, the direction of the arcs should respect the direction of the path from a CS to another. If there is no path from one CS to another, that means that the equivalent direct impact is equal to 0.

$$Imp(x/y) = 1 - (Criticality(x) - Criticality(y)) \times Frailty(y) \tag{4.6}$$

With:
$Imp(x/y)$: representing the direct impact of x on y.

$$\begin{array}{c} \\ S_1 \\ S_2 \\ S_3 \\ S_4 \\ \vdots \\ S_k \end{array} \begin{array}{c} \begin{array}{cccccc} S_1 & S_2 & S_3 & S_4 & \cdots & S_k \end{array} \\ \begin{pmatrix} I_{11} & I_{12} & I_{13} & I_{14} & \cdots & I_{1k} \\ I_{21} & I_{22} & I_{23} & I_{24} & \cdots & I_{2k} \\ I_{31} & I_{32} & I_{33} & I_{34} & \cdots & I_{3k} \\ I_{41} & I_{42} & I_{43} & I_{44} & \cdots & I_{4k} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ I_{k1} & I_{k2} & I_{k3} & I_{k4} & \cdots & I_{kk} \end{pmatrix} \end{array} = \mathsf{M}$$

Figure 4.5: The direct impacts matrix illustration.

4.3.5 The Direct Impacts Matrix

The idea behind the conception of the impacts matrix is to map all the impacts of every CS on each one of the rest of CS forming the SoS. Accordingly, the matrix is a useful tool to gather all the impact values in one expression.

Figure 4.5 illustrates the format of the direct impacts matrix, with:
S_i: represents a CS.
k: represents the total number of CS forming the SoS.
I_{ij}: represents the direct impact value of the CS on the CS . With $I_{11} = I_{22} = I_{33}...I_{kk} = 1$ as the impact of a CS on itself is 100 %.

4.3.6 The Permanent of the Impacts Matrix

The formal definition of the permanent of a $k \times k$ matrix is expressed as following Caro-Lopera et al. (2013):

$$Per(M) = \sum_{\sigma \in S_k} \prod_{i=1}^{k} a_{i,\sigma(i)} \tag{4.7}$$

It is a standard matrix function that is used in combinatorial mathematics in order to determine an index Jense and Gutin (2000), Jurkat and Ryser (1966), Harary and Maybee (1985). While the permanent is used in order to transform the impacts matrix into an indicator. Contrary to the determinant, the permanent calculation does not include any negative sign. Thus, the loss of information is avoided. Besides, it can be considered as a safe way to preserve all the information within the matrix.

4.3.7 The Structural Resilience Indicator

The formal definition of the structural resilience indicator is:

$$SRI = 1 - \frac{1}{Per(M)} \tag{4.8}$$

The structural resilience indicator represents the resilience level of the studied SoS structure (representing the economic infrastructure of the region, country, etc.). It is a real number between 0 and 1. It is possible to take the same number and multiply it by 100, the result is the economic structure's resilience rate.

The more the structural resilient indicator is close to '1' the more the SoS structure is resilient. Accordingly, the more it is close to '0' the less it is resilient.

4.4 Inherent Structural Resilience Constraints

Practically, there are some constraints to manage for a complete structural resilience assessment. In this context, they represent the SoS structural challenges that need to be considered in the structural conception and analysis. They are:

- The competition of needs
- The evolution of needs

Another constraint can also be considered; it is resource availability. It is an important criterion for the conception, design, implementation, operation, sustainment, etc. And it includes financial (capital investment), knowledge, skills, etc.

4.4.1 The Competition of Needs

The biggest problem with needs is that they compete with each other. A set of needs tend to call for a number of solutions, competing with each other. In the conception phase, it is crucial to anticipate and manage in a way that targets the right balance. This involves sacrificing the complete individual satisfaction and replace it with an acceptable degree to be achieved in order to cover all the needs Jamshidi (2008b).

4.4.2 The Evolution of Needs

Judging a solution cannot be complete without judging the circumstances that drive the need for it. As an example, consider the problem of quick communication over distances. This need was satisfied in the 19^{th} century with the telegraph. While the telegraph was an adequate solution, it would become inadequate today, as the needs have evolved. While the basic need for long-distance communication still exists today, it has become much more elaborate, due in large part to the advancement of technology and expectations of users Jamshidi (2008b).

Time is required for solutions to take shape. Besides, the need, that is present in the prime of the system's lifecycle, is really important. When a need is present at the as the available resources, circumstances are right for a potential solution. And when the circumstances persist for a long time, the solution to a problem can be realized Jamshidi (2008b).

4.5 Modeling and Implementation

As in the previous chapter, this section's objective is to model the presented approach using UML for an eventual prototype. The aim is to provide a standard visualization of the system's conception.

In this section, a visualization of the system's conception is done through two different classes. A structural representation is done using the class diagram in order to provide a representation of the systems static structure.

And a behavioral representation is done using both use case and activity diagrams. The idea is to elucidate the activities, system's components, the interactions, the system's behaviors and external interfaces related to the execution of the theory.

4.5.1 The Class Diagram

The first diagram to be detailed is the class diagram. It's a structural diagram that will contribute to describe the system's structure by showing classes, their attributes and methods in addition to the relationships among objects. It is a useful tool for object-oriented and data modeling.

Figure 4.6 illustrates the proposed model's class diagram. It embraces twelve classes. Each class also contains a set of private attributes in order to describe the instances of the classes. The classes are: SoS, system, directImpact, interdependency, risk, emergence, vulnerability, barrier, technicalBarrier, organizationalBarrier, functionalBarrier and geographicalBarrier.

Accordingly, three sorts of relationships are used in the diagram. Some classes are related to each other by inheritance, this kind of relationships is depicted by an arrow. The arrows are directed towards the parent class.

The subclasses inherit all the attributes and methods. In the Figure 4.6, technicalBarrier, organizationalBarrier, functionalBarrier and geographicalBarrier classes inherit from the parent class barrier. In addition, the class "barrier" itself along with "vulnerability" and "emergence" inherit from the parent class "risk".

Another relationships type included in the diagram is the classic association. They are depicted by a simple line linking two classes. This kind of relationships includes multiplicity, which provides the possibility to set numerical constraints. For example, every CS can have numerous interdependencies with other CS or none at all, while every interdependency relates to only two CS.

The third relationship's type included in the diagram is composition. It illustrates the components forming a class or an instance. In the model's class diagram, the relationship shows that the SoS class is composed of the system class.

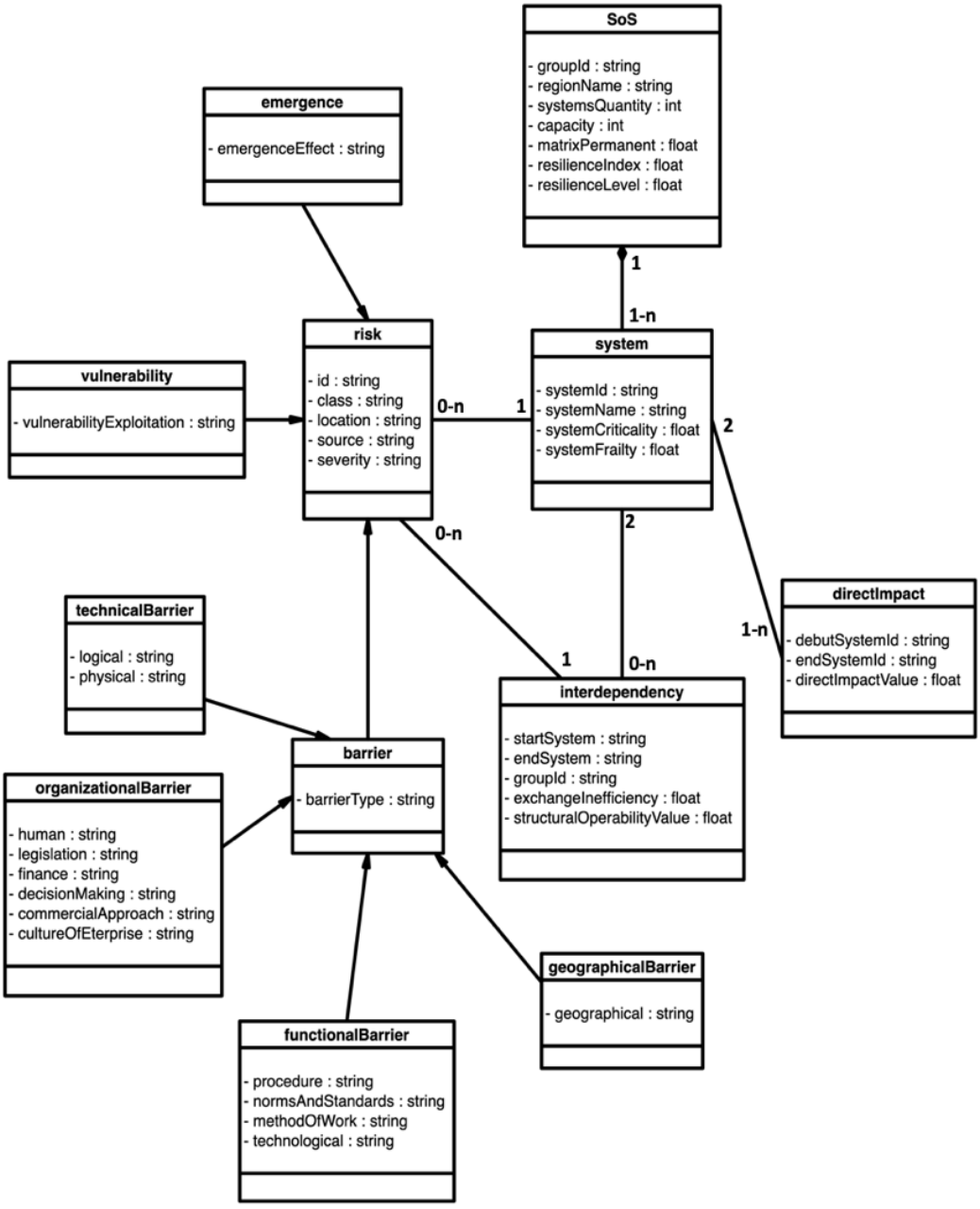

Figure 4.6: The model's class diagram.

The following subsections provide a representation of the behavior of the model. They present the set of action made available by the system using use case and activity

diagrams.

4.5.2 SoS Constituents Management: Use Case Diagram

One of the important available actions in the model is the ability to create SoS. This creation involves two other inherent actions, which are: the creation of both the CS and interdependencies. Figure 4.7 illustrates the use case diagram of the SoS, CS and interdependencies management.

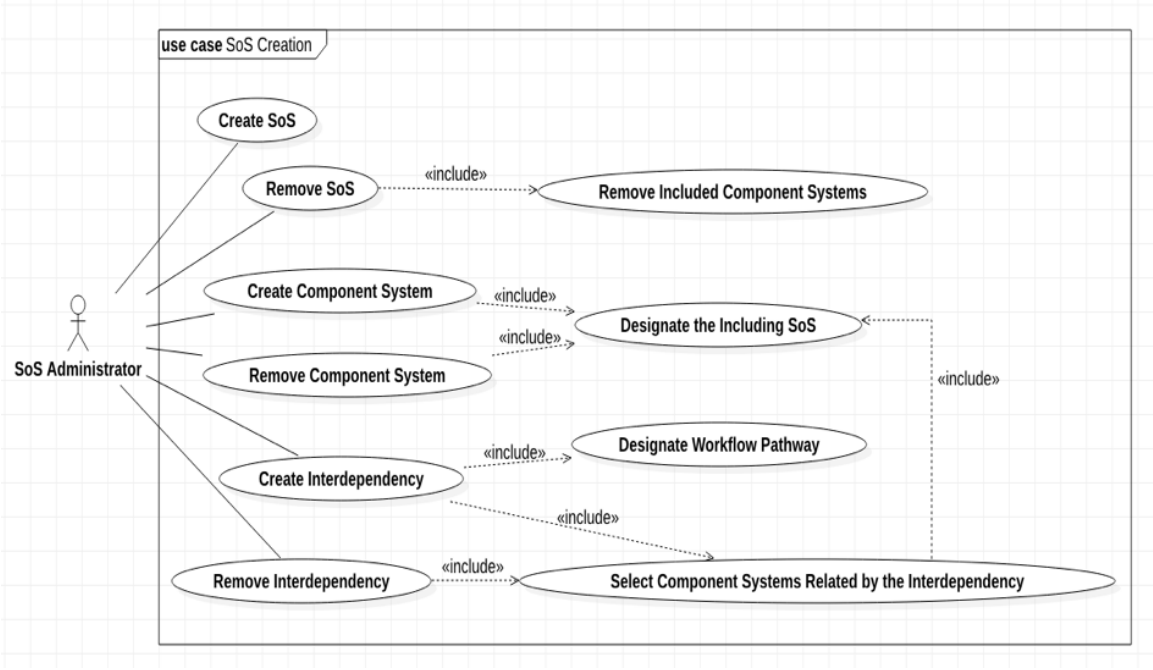

Figure 4.7: The use case diagram of the SoS, CS and interdependencies management.

The user or SoS administrator has the ability to create as many SoS as he wants. He is able to remove SoS as well. The creation of the SoS is correlated with the creation of the CS and interdependencies that are planned to be included amid it. Their creation includes the designation of the including SoS. Furthermore, interdependencies creation also includes the designation of the workflow pathways.

Correspondingly, removals are also correlated. The removal of a SoS triggers the removal of all CS and interdependencies within the SoS. In addition, the removal of an interdependency is done by selecting CS related by this interdependency, with respect to its flow and its direction.

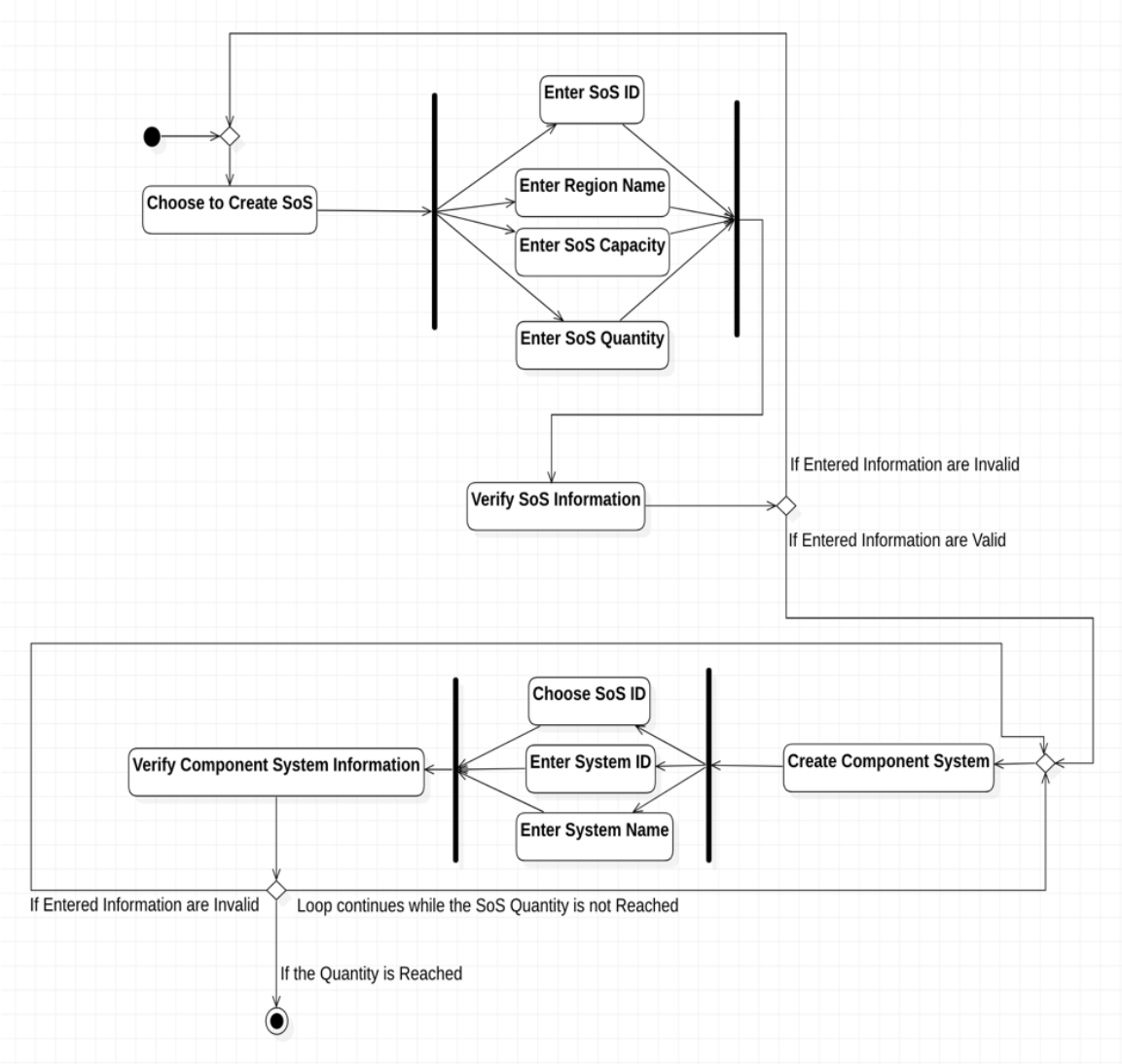

Figure 4.8: SoS constituents management activity diagram.

4.5.3 SoS and Cs Creation: Activity Diagram

Figure 4.8 illustrates the activity diagram of the SoS, CS and interdependencies creation processes. This diagram depicts all the actions and activities in addition to the flow linking them.

Here is an explanation of the process described in the figure. After the execution of the choice to create an SoS, the user needs to enter information regarding it. The entered information is checked if there is a problem regarding the entered information, the user needs to reenter the required information. The process repeats itself until entering a correct description of the SoS.

The reasons behind the non-validation of information are various, it could be related to some constraints (e.g. the capacity should be more than the quantity) or the entered information are already affected to an existing SoS.

On the other hand, if entered information is correct, the user is redirected to the creation of CS. The user keeps entering information concerning CS until achieving the required quantity. In addition, all the entered information is checked, and the entered information could be valid or invalid depending on the established constraints.

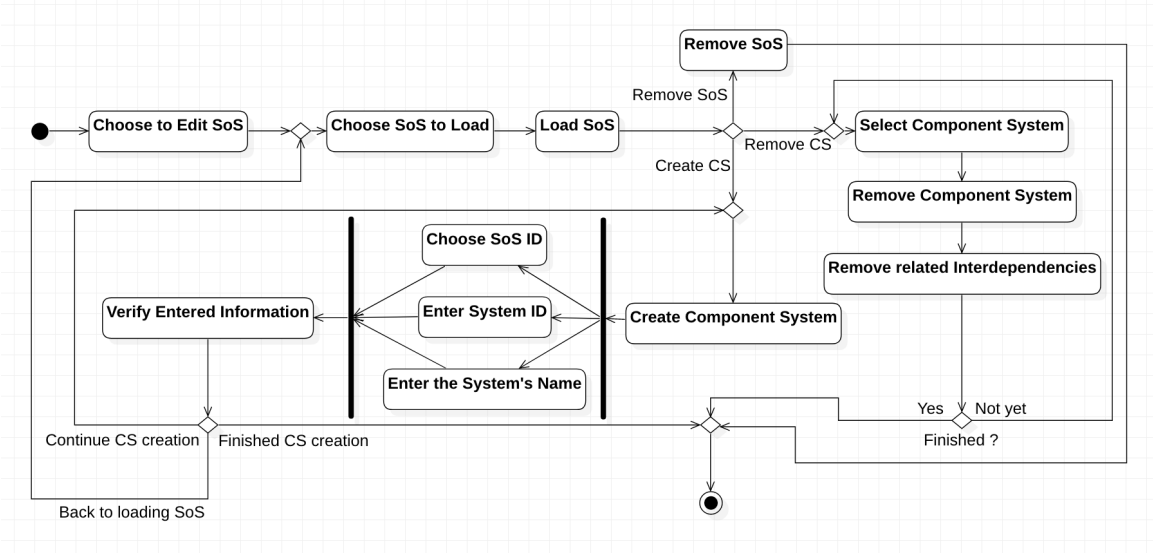

Figure 4.9: The activity diagram of the SoS and CS edition.

Eventually, the result of this process is the creation of an SoS and the embraced CS.

4.5.4 SoS and CS Editing: Activity Diagram

Figure 4.9 describes the activity diagram of the SoS and CS editing. It describes the process in addition to a set of actions and activities flows to edit previously created SoS and CS.

The process launches by choosing the SoS to be edited then loading it. Next, the system offers three possibilities to the user. First one is to remove the selected SoS. The second is to select a CS, then delete it. This triggers the removal of all interdependencies related to the selected CS. The third is to create a new CS.

The process described by the activity diagram in Figure 4.9 is done with iterations. Each iteration involves only one interdependency.

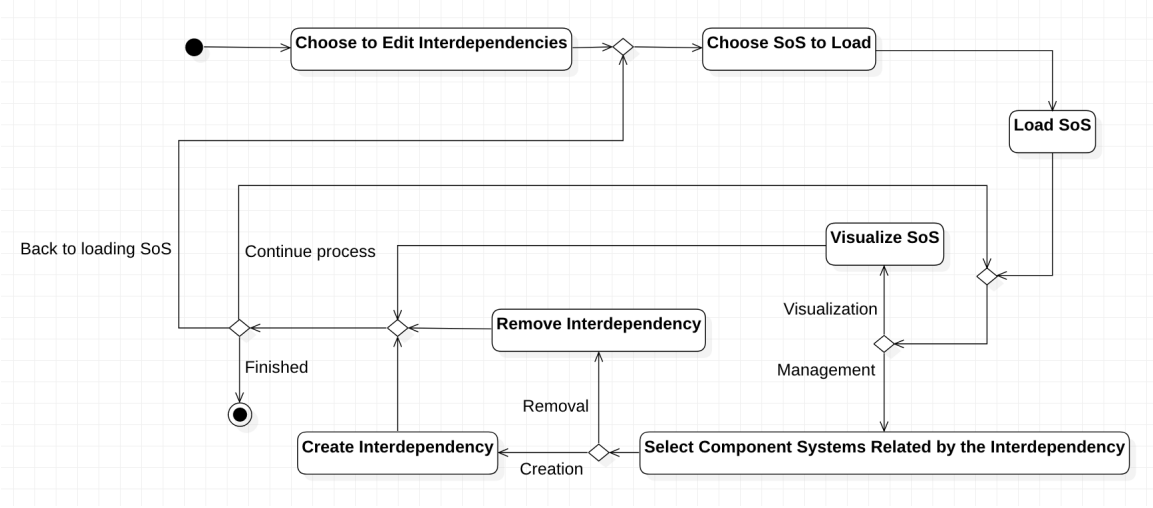

Figure 4.10: Interdependencies editing activity diagram.

4.5.5 Interdependencies Editing: Activity Diagram

Figure 4.10 describes the interdependencies creation activity diagram. It describes the process in addition to set of actions and activity flows for the creation of interdependencies amid a designated SoS.

After choosing to edit interdependencies, the first action, that needs to be performed, is to load the SoS that will be the subject of the alterations. Once the SoS is fully loaded, the system offers two possibilities to the user.

The first one is to visualize the SoS. The second option is to select two CS and then create an interdependency between them or remove an existing one. It is important to note, that interdependencies creation and removal is done with respect to the workflow pathways.

The processes of interdependencies creation and removal are done iteratively. Each iteration involves only one interdependency. The visualization of the SoS can be effectuated after every alteration. Besides, alteration of other existing SoS can be done by loading them.

4.5.6 Structural Resilience Assessment: Use Case Diagram

Figure 4.11 illustrates the actions performed in order to assess the structural resilience of SoS. This action is triggered by one of three cases. The first case is scenario simulation. The user creates a SoS and inherent components without storing it in the

database and launches calculations to evaluate its structural resilience.

The second is to load an SoS already stored in the database where the CS and interdependencies are already created. Then, it is possible to launch the calculations in order to evaluate the structural resilience level of the selected SoS.

The third is to load two SoS, then launch calculations. The idea behind this option is to provide the possibility to compare simultaneously the structural resilience level of both of them.

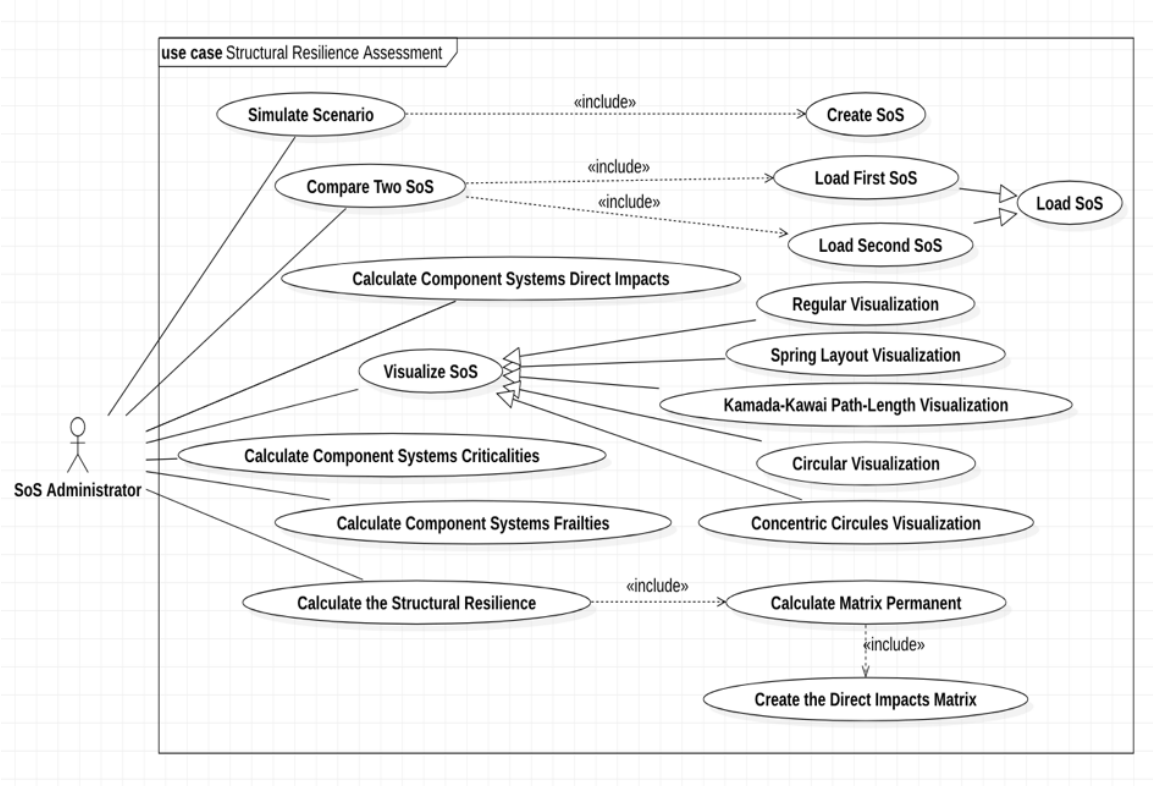

Figure 4.11: Structural assessment use case diagram.

Regarding the calculations, they are done following the process depicted in previous sections. It starts by calculating criticalities and frailties. Next is the calculation of direct impacts within the SoS. Then, the creation of the direct impact matrix and its permanent calculation. The final step is to calculate the structural resilience.

The system also offers a set of possibilities to visualize SoS, whether it is simulated or loaded. The visualization options are:

- Regular visualization
- Spring layout visualization

- Kamada-Kawai Path-length visualization
- Circular visualization
- Concentric circles visualization

4.5.7 Loading SoS: Activity Diagram

Figure 4.12 presents the activity diagram of the calculations launching after SoS loading action. This activity starts by choosing the SoS to be loaded, then, loading it.

When a SoS is loaded, two options become available. The first one is evidently the possibility to launch all the calculations regarding the structural resilience. Results are also generated. The second one is to visualize the loaded SoS. The SoS visualization is correlated to the generation of the information regarding the structure (i.e. CS number, interdependencies number, etc.)

4.5.8 SoS Comparison: Activity Diagram

The SoS comparison starts by loading two SoS. Once it is done, one can evaluate their structural resilience. Then, results are generated, as a result, the user can figure out which one is structurally more resilient.

Figure 4.13 describes the comparison process. It is similar to the previous one, the only difference is that two SoS are loaded and not just one.

4.5.9 Scenarios Simulation: Activity Diagram

Scenario simulation is useful in case that the SoS administrator wants to simulate a SoS before creating it. This action includes all the properties that provide the loading action. See Figure 4.14.

In this case, the SoS is not created. Consequently, the simulated SoS should be created, in addition to its CS and interdependencies. After the SoS creation, the user can launch the resilience evaluation and visualize the created SoS. However, the created SoS will not be stored in the database.

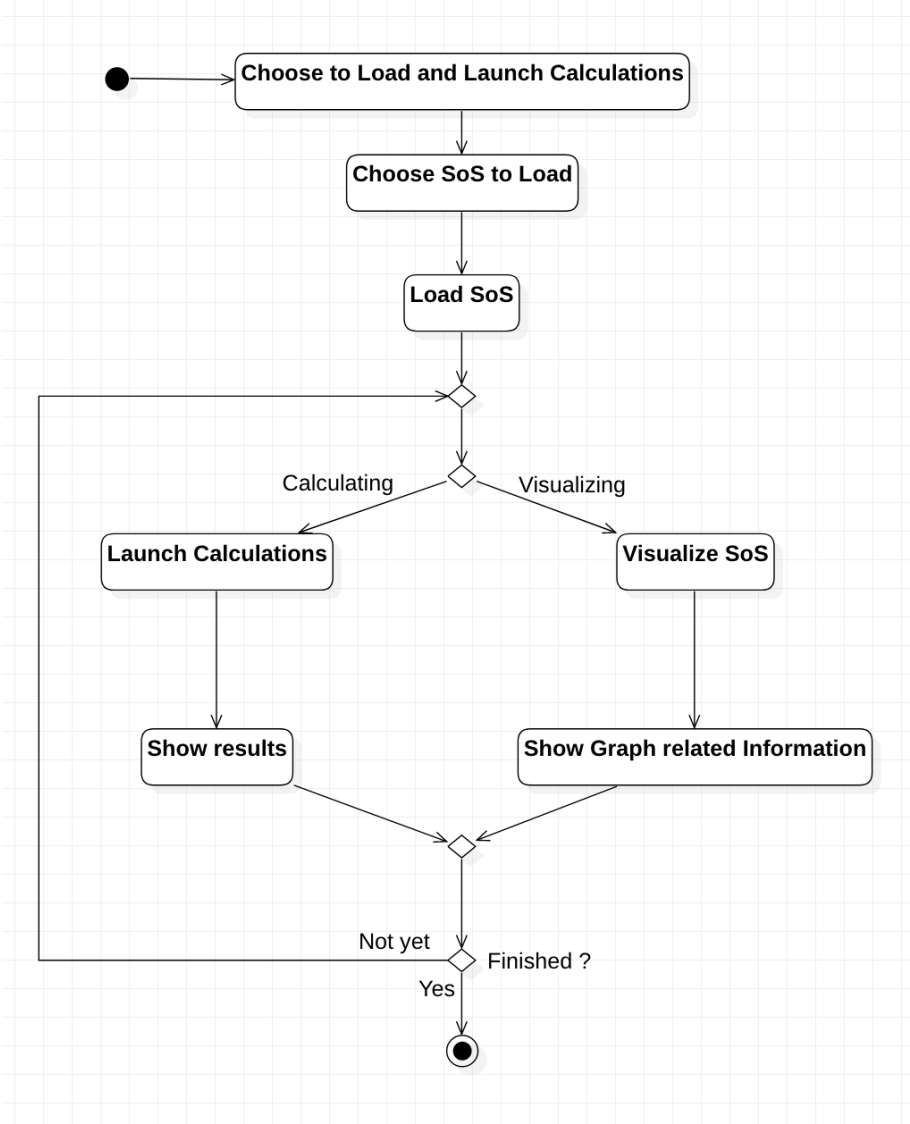

Figure 4.12: Loading a SoS and launching structural resilience evaluation activity diagram.

4.5.10 Risk Supervision: Use Case Diagram

A complementary action can be added for a more effective SoS structural resilience assessment is risks supervision. An evaluation of structural destabilizations catalyzers can also be useful as SoS has a special structure with special properties.

It is crucial to inspect the potential sources of risks that could disturb the operational and functional return of SoS.

Figure 4.15 describes the risk supervision use case. It includes three main actions:

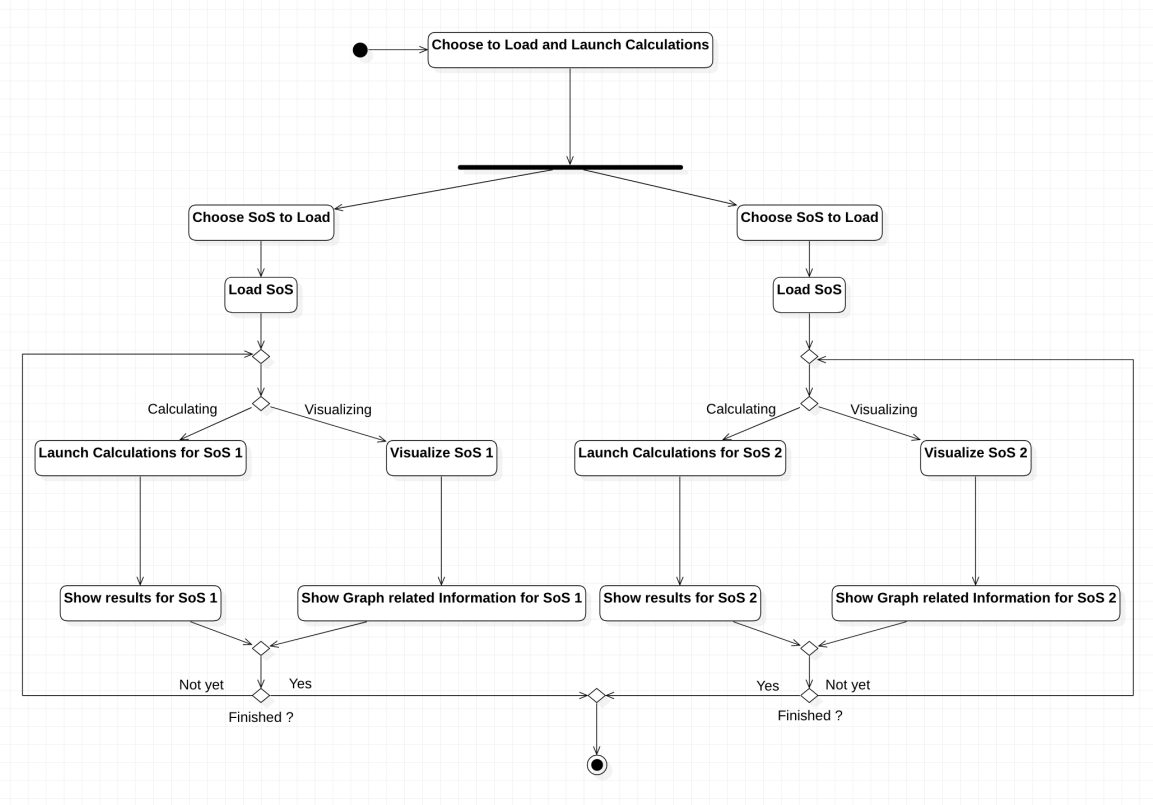

Figure 4.13: SoS comparison activity diagram.

- Risk identification: which includes the location of the risk's target and the identification of its origin.

- Risk analysis: this includes risks classification, severity quantification, duration estimation. These properties are very useful for analysis. They help to elaborate pertinent countermeasures.

- Risk elimination: which elaborates and implements effective countermeasures to face the risks targeting the SoS.

4.6 Conclusions

This chapter is an attempt to respond to the concerns related to SoS reliability through resilience assessment by managing risks and analyzing the SoS structure. An approach is proposed to anticipate risks, their influences and impacts. It contributes to the quantitative anticipation of SoS resilience. This also implicitly embraces a step

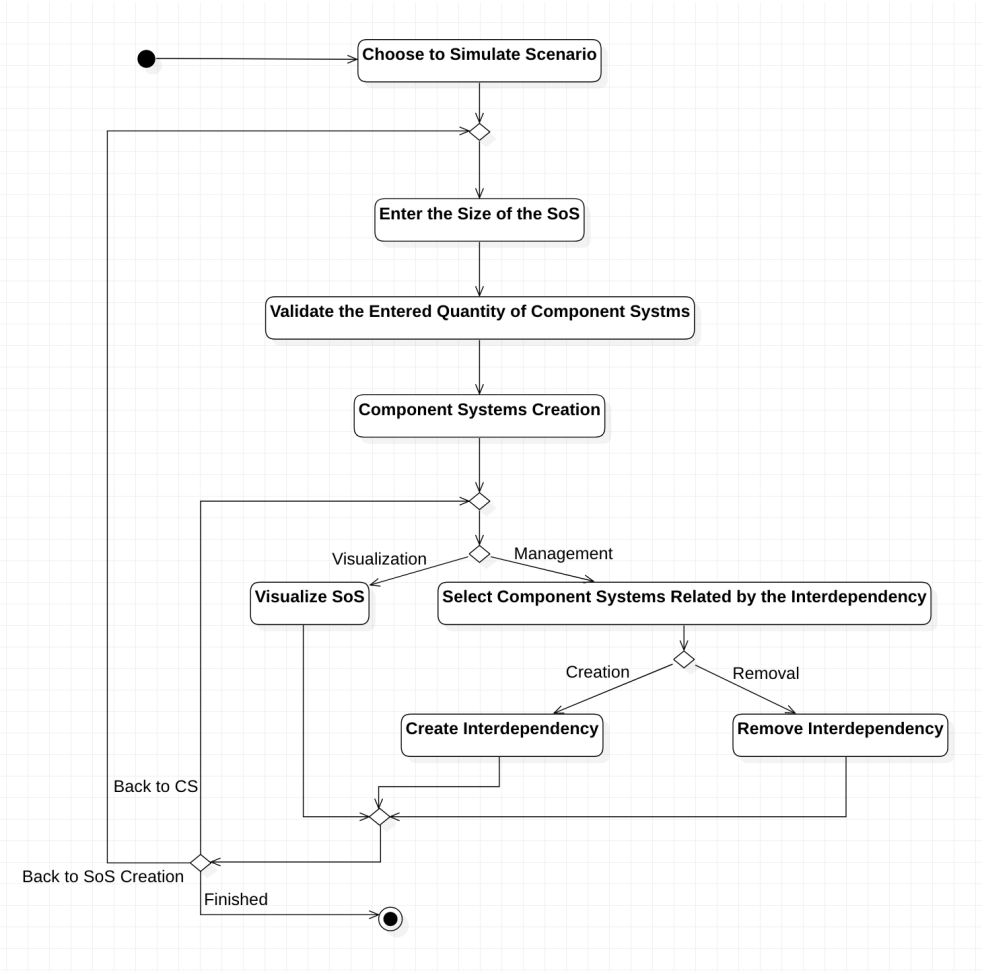

Figure 4.14: Scenario simulation activity diagram.

towards reliability evaluation and enhancement. Reliability and resilience concepts are two strongly related notions.

The presented approach aims to address the anticipation of risks in SoS through two complementary approaches: one dedicated to risks management and the other to structural analysis.

The risks management approach is also based on two important steps: risks classification, which is based on their natures and sources, and risks monitoring, which is conceived to evaluate, analyze and supervise risks representing the catalyzers of destabilizations.

While the structural analysis starts with functional interdependencies analysis. Next, it estimates the dependency of the process continuity on every CS, thanks to the vulnerability and criticality measures of each CS. Then, it estimates the failure

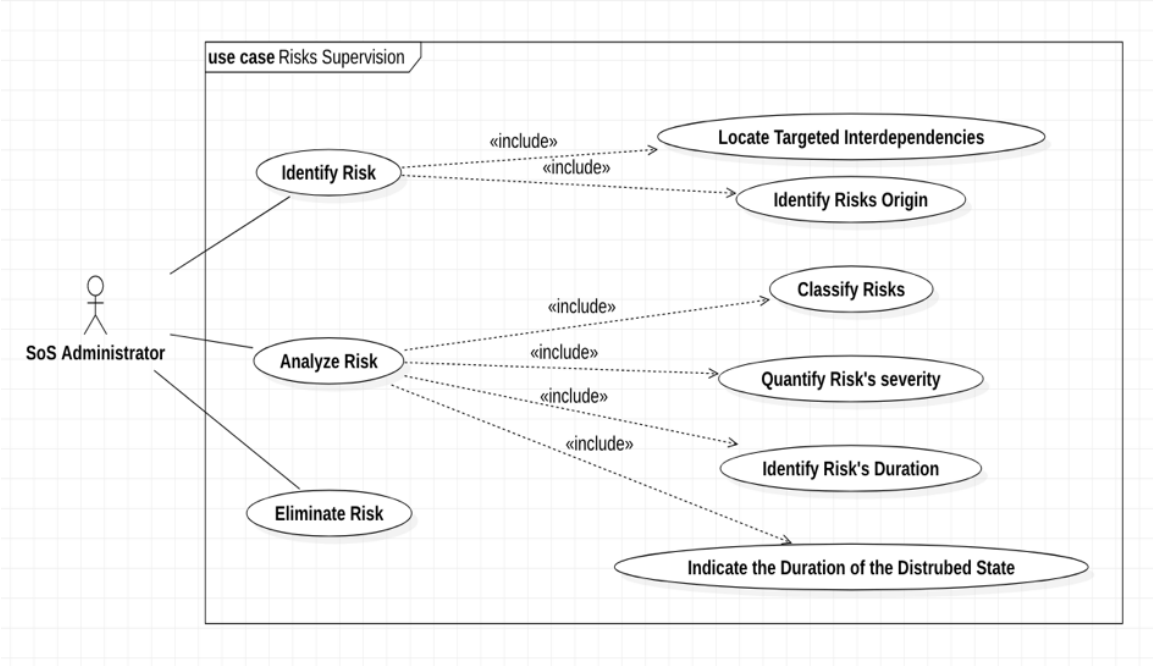

Figure 4.15: Risk supervision use case.

impact of each CS in addition to the SoS susceptibility to a CS in order to evaluate the structural resilience of the whole SoS.

Structural analysis metrics contribute to the anticipation of the resilience measurement by locating impactful (and vulnerable) CS and predicting their influence (and their susceptibility) on (to) the SoS structural composition. This leads to the estimation of SoS survivability after each CS failure.

This location can be followed by the reorganization of the SoS structure in order to demean the impact of CS on the process continuity and the overall performance of the global SoS.

Chapter 5

SoS and Structural Analysis as a Basis to Regional Resilience Assessment

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5.1 Introduction

The concept of resilience is inherent to the system's capability to forecast and resist disturbances Peng et al. (2017), Jianming et al. (2012), to preserve the same operability in case of occurrence, and improve itself using accessible resources Peng et al. (2017).

In the context of regional resilience, focus is on the conception of metrics to evaluate the ability of regions to resist economic shocks Östh et al. (2015), Caschili et al. (2015). Still, less attention is given to structures, interactions and workflow pathways within the spatial object in the development of resilience metrics Östh et al. (2015).

In an attempt to combine resilience with the spatial object's structure in addition to the embraced workflow pathways, some approaches are proposed to the assessment of structural resilience.

The combination of the resilience concept with the spatial object aims to assess and measure the regional development and evolution. It also helps to anticipate and evaluate the impacts of threats targeting an area to elaborate plans and take actions to mitigate their impacts. This combination also takes into account the region's inner behaviors, culture and policy contribution Foster (2007), Christopherson et al. (2010), Dawley et al. (2010), Iordan et al. (2015), Shaw and Maythorne (2013).

In this chapter, a prototype is designed in order to process the structural resilience assessment. Considering spatial objects, it has been used to conduct experiments on real-based industrial infrastructures approached as SoS.

The remaining part of this chapter is organized as follows:

- Section 2 introduces the resilience concept and its combination with the spatial object.
- Section 3 outlines implementation tools, libraries and packages.
- Section 4 details the simulation of two different case studies through the proposed prototype.
- Section 5 presents additional remarks and potential extension.
- The last section draws conclusions.

5.2 Combining the Resilience Concept with the Spatial Object

Maintaining resilience for regions namely the ability to anticipate, prepare for, respond to, and recover from diverse disturbances, natural and man-made disasters became a necessity and a new subject of urban and regional planning Peng et al. (2017).

Currently, academics of international urban and regional planning, in Europe, North America, Asia, etc. have established diverse institutions in order to address all aspects of regional resilience. Resilience in regional and urban contexts have attracted increasing attention from the research community Peng et al. (2017).

The combination of the concept of resilience with the spatial object aims to assess regional development. Its main added value goes from anticipating and evaluating threats targeting an area to elaborating plans and taking actions to mitigate their impacts Peng et al. (2017). It also embraces the region's inner behaviors, culture and policy contribution Foster (2007), Christopherson et al. (2010), Dawley et al. (2010), Iordan et al. (2015), Shaw and Maythorne (2013).

Accordingly, the region should be able to anticipate the prospected repercussions of the potential threats to mitigate the repercussions on the special object, to return to a stable state after the shocks and to recover with a more efficient balance Peng et al. (2017).

In Peng et al. (2017), authors claim that regional resilience's basic meaning is based on four abilities:

- Expectation
- Resolving threats
- Self-maintenance in case of shock occurrence
- Regions' ability to enhance their own abilities

Besides, resilience changes regional development and competitiveness concepts Peng et al. (2017), Bristow (2010), Hudson (2009) as it is also related to regional ecology, economy and society Berkes et al. (2008), Walker et al. (2002). Accordingly, there are three characteristics that define regional resilience: stability, self-organization and innovation Peng et al. (2017), Dabson et al. (2012), Foster (2007), Wilbanks (2008), Zhong and Wei (2010), Hill et al. (2008).

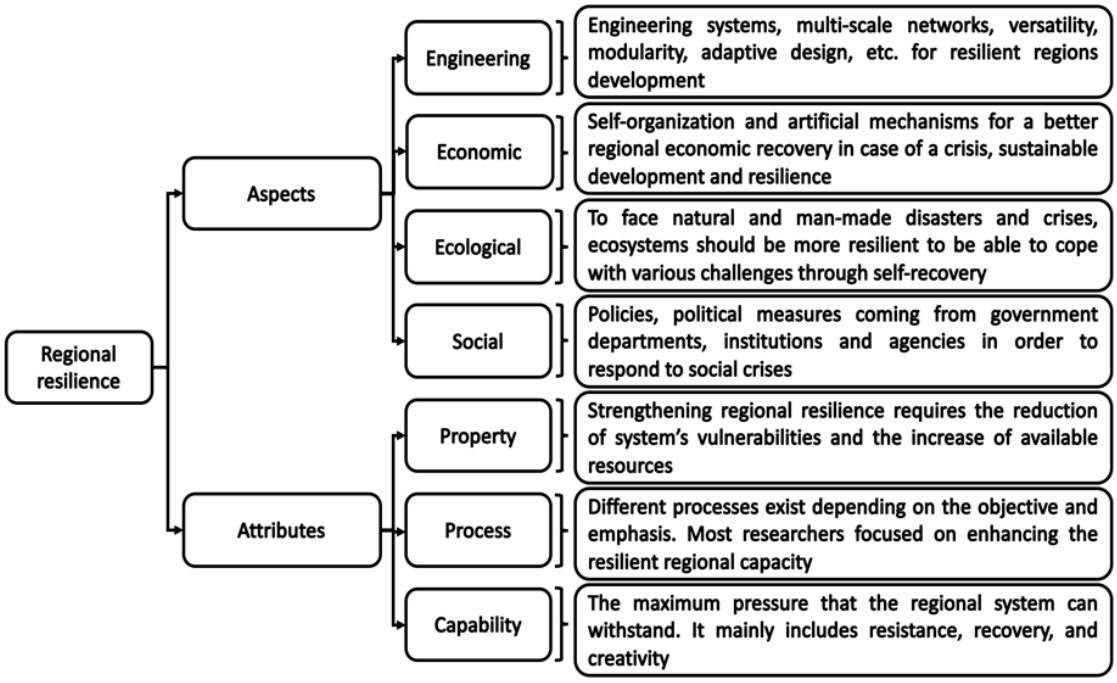

Figure 5.1: Regional resilience aspects and attributes taxonomy. Adapted from Peng et al. (2017).

Based on the literature review in Peng et al. (2017), two important notions siring the concept of regional resilience need to be distinguished: regional resilience aspects and attributes. Figure 5.1 illustrates the regional resilience aspects and attributes taxonomy.

5.2.1 Regional Resilience Aspects

Regional resilience has known remarkable progress in numerous domains, which are exemplified in the following four aspects: engineering, economic, ecological and social. Note that some of the used nominations and their definitions are inspired by Peng et al. (2017).

Engineering Aspect

Regional resilience engineering aims to reach the swift recovery of infrastructures and population from disasters Peng et al. (2017), Jianming et al. (2012). Numerous countries have recognized that the improvement of the infrastructure directly contributes to the regional resilience enhancement.

It represents a great potential path for recovery (or bouncing back Peng et al. (2017)) and reflects the projection of robustness, recovery ability and speed Holling (1973), Crespo et al. (2013), similarly to the swing mode proposed in Zhong and Wei (2010), Kim et al. (1999), Folke (2006), Pimm (1984), Walker and Salt (2012), Yan et al. (2012), Ahern (2011).

Economic Aspect

This emerged after the financial crisis of 2008, and currently, it represents one of the subjects of interest of western researches. It targets regional recovery and sustainable development Hudson (2009), Christopherson et al. (2010), Boschma (2015), Carpenter et al. (2001), Martin et al. (2015), Simmie and Martin (2010), Yan et al. (2013). Some researchers see that regional resilience represents the ability of a region to resist internal crises, while recovery and creativity are related to the capacity to adapt to new external situations and a new environment Adger (2000), Zhong and Wei (2010). Besides, the regional economic resilience development is not only influenced by industrial structures and infrastructures. It is also influenced by the outcome of policy management and allocation Peng et al. (2017).

Accordingly, the region's economic recovery process can be done through one of four different reactions Peng et al. (2017):

- Resuming the original growth rate
- Restoring the original growth rate, but with a lower level of development
- Failing to return to the original growth rate
- Achieving a higher level of growth rate

Correspondingly, several studies prove that the factors that shape the regional economic disparities are path independence, path creation, policy support and economic diversity Martin (2010). De facto, there are three categories of economic diversity.

The first one called structural diversity. It aims to reduce the destructive power of regional economic crisis, prevent regional locking-in and facilitate the rapid recovery of the regional economy by adopting multiple industrial structures Martin (2010).

The second one is called typological diversity. A diversified region can enable the transfer and dispersion of external shocks into different directions and contribute to regional economic recovery and adaptation Dawley et al. (2010).

The third one is called implementing diversity. Implementations, such as structural adjustment, improving technology, rational development of ecological resources and environmental protection, can considerably improve regional resilience.

Ecological aspect

Self-recovery is no longer an option for the ecosystem to cope with the various changes caused by climate change, resource depletion and environmental quality recession Peng et al. (2017). Therefore, ecological resilience is a very urgent subject that requires the mobilization of all research community.

In fact, ecological resilience can be classified into two categories. The first one is called the static equilibrium. It holds the ecosystem steadily resilient Xiuqi and Peihong (2007). It absorbs interferences before reaching dynamic equilibrium and emphasizes the process of returning to normalcy Berkes et al. (2000), Folke (2006). This is done without changing the original functions Adger (2000), Xiuqi and Peihong (2007).

The second one is the steady-state and it represents the ability of the ecosystem to update, reshape, and develop consistently and continuously with an acceptable speed of recovery Adger (2000), Xiuqi and Peihong (2007), Folke (2006), Yan et al. (2012), QIU et al. (2011), WANG et al. (2010).

Social aspect

The social resilience is principally related to government-centered institutions and agencies and their ability to respond effectively to economic political, ecological and social crises Foster (2007). Social crises are mostly intangible, they include policy changes in developing countries, economic changes affected by financial crises, demographic changes by an aging population and unbalanced population mobility, environmental changes under a wide range of population pressure, agriculture and water resources depletion, as well as the technological transformation that is gradually changing the traditional way of life Peng et al. (2017), Mazur (2013).

Two different classes of social resilience can be distinguished. The first one is the ability to recover from the effect of a crisis, emergent event, shock, etc. and restore the original state. While the second represents the ability to bounce forward from the effect of the crisis, emergent event, shock, etc. which means to anticipate and be prepared for the coming shocks Cho et al. (2011).

5.2.2 Regional Resilience Attributes

Many researchers put forward different components for regional resilience Wilbanks (2008), WANG et al. (2010), Cho et al. (2011). They can be classified into three categories: regional resilience properties, process and abilities Peng et al. (2017), Jianming et al. (2012), Tongyue et al. (2015).

Regional Resilience Properties

Regional resilience properties are the system's vulnerability and resource availability. The system's vulnerability includes physical, economic and social damages Dabson et al. (2012), while resource availability refers to resource redundancy Dabson et al. (2012) and availability amidst the region and during the development progress Peng et al. (2017).

The improvement of regional resilience requires simply the decrease of systems' vulnerabilities and the multiplication of the resources amid the region. It is also helpful to improve the cooperation between the government's departments for the enhancement of resilience.

Regional resilience Processes

Numerous processes exist in literature, most researches focus on the final result of the process which should imply regional resilience enhancement. There are two processes detailed in Peng et al. (2017): the first one is Resistance-Renewal-Recovery-Reorientation process Martin (2011) and the second one is Shock-Capacity-Impact-Trajectory-Outcome-New Capacity framework Dabson et al. (2012).

Regional Resilience Abilities

The resilience abilities represent the maximum pressure that the regional system could possibly resist, technically, it includes three criteria: resistance, recovery and creativity Peng et al. (2017), Frommer (2013), Maguire et al. (2007), Weick and Sutcliffe (2011).

- Resistance refers to the capability of the region to withstand shocks without changing its structure and inner functions Peng et al. (2017), Frommer (2013).

- Recovery describes the function whereby a region can bounce back to its pre-shock state within a given duration Frommer (2013). The faster it gets to its initial state the more resilient it is Peng et al. (2017), Frommer (2013), Maguire et al. (2007).

- Creativity represents the capability of the system not only to recover to its initial state but to achieve a higher and better state as a mean to adapt itself to new situations Frommer (2013), Maguire et al. (2007). Highly resilient systems have a self-learning ability to keep continuously improving from the experienced circumstances Peng et al. (2017), Frommer (2013), Maguire et al. (2007).

5.3 Implementation Tools, Libraries and Packages

In this section, a prototype is proposed. The idea is to implement the previously presented model. An application will be conducted to two different case studies from the French economic infrastructure.

The prototype is developed using Python language. It is an interpreted, high-level, general-purpose programming language. It provides constructs that enable clear programming on both small and large scales and it has fewer syntactical constructions than other languages. It is interpreted because it is processed at runtime by an interpreter. This means that there is no need to compile a program before executing it. It is interactive because the programmer interacts directly with the interpreter to write programs.

Python is dynamically typed and garbage-collected. It supports multiple programming paradigms, including procedural, object-oriented, and functional programming. Python also features a comprehensive standard library.

5.3.1 Modules, libraries and packages

A set of modules, libraries, and packages is also used in order to implement and develop the proposed model. An explanation of all of them is given in this subsection.

Here is a list of all the used libraries modules, libraries, and packages:

- Tkinter Module

- Matplotlib Library

- Numpy Library
- Connector/Python
- NetworkX Package

Tkinter Module

Tkinter is a Python binding to the Tk GUI toolkit. It is Python's standard GUI (Graphical User Interface). With standard representing custom or convention that has achieved a dominant position by public acceptance or market forces.

Tkinter is included with standard Linux, Microsoft Windows and Mac OS X installs of Python. It is implemented as a Python wrapper around a complete Tcl interpreter embedded in the Python interpreter. Tkinter calls are translated into Tcl commands which are fed to this embedded interpreter, thus making it possible to mix Python and Tcl in a single application.

Matplotlib Library

Matplotlib is a Python 2D plotting library which produces publication quality figures in a variety of hardcopy formats and interactive environments across platforms. Matplotlib can be used in Python scripts, the Python and IPython shells, the Jupyter notebook, web application servers, and four GUI toolkits.

It helps to generate plots, histograms, power spectra, bar charts, errorcharts, scatterplots, etc. The used version of this library is Matplotlib version 3.0.3.

Numpy Library

Numpy is considered as one of the most popular machine learning library in Python. This interface can be utilized for expressing images, sound waves, and other binary raw streams as an array of real numbers in N-dimensional.

For implementing this library for machine learning having knowledge of Numpy is important for full stack developers.

Besides, it has several useful features:

- Interactivity.

- It simplifies complex mathematical implementations.
- It is widely used, hence a lot of open source contributions.

In this work, Numpy is used in order to simplify the mathematical implementations of the used equations and calculations.

Connector/Python

MySQL Connector/Python is a standardized database driver for Python platforms and development. It enables Python programs to access MySQL databases, using an API that is compliant with the Python Database API Specification v2.0 (PEP 249). It is written in pure Python and does not have any dependencies except for the Python Standard Library.

MySQL Connector/Python includes support for:

- Almost all features provided by MySQL Server up to and including MySQL Server version 5.7.
- Connector/Python 8.0 also supports X DevAPI. For documentation of the concepts and the usage of MySQL Connector/Python with X DevAPI, see X DevAPI User Guide.
- Converting parameter values back and forth between Python and MySQL data types, for example, Python datetime and MySQL DATETIME. You can turn automatic conversion on for convenience, or off for optimal performance.
- All MySQL extensions to standard SQL syntax.
- Protocol compression, which enables compressing the data stream between the client and the server.
- Connections using TCP/IP sockets and on Unix using Unix sockets.
- Secure TCP/IP connections using SSL.
- Self-contained driver. Connector/Python does not require the MySQL client library or any Python modules outside the standard library.

NetworkX Package

NetworkX is a Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks.

NetworkX has several useful features:

- Data structures for graphs, digraphs, and multigraphs
- Many standard graph algorithms
- Network structure and analysis measures
- Generators for classic graphs, random graphs, and synthetic networks
- Nodes can be "anything" (e.g., text, images, XML records)
- Edges can hold arbitrary data (e.g., weights, time-series)
- Open source 3-clause BSD license

5.3.2 Anaconda and VS Code

Anaconda is a complete, open source package with a community of over 11 million users worldwide. It is easy to download and install and is supported by all of the most used operating systems: Linux, macOS, OS X and Windows.

Anaconda uses Conda to manage libraries, dependencies and environment as it installs and runs them swiftly. Conda also creates, saves, loads and switches between environments. In this chapter, Anaconda Navigator is used. It is a desktop GUI system that includes various IDE's shown Figure 5.2.

Accordingly, for source code editing, VS Code is used. It includes support for debugging, embedded Git control, syntax highlighting, intelligent code completion, snippets, and code refactoring. It is also customizable, so users can change the editor's theme, keyboard shortcuts, and preferences. The source code is free and open source and released under the permissive MIT License. See Figure 5.3.

5.3.3 MySQL Workbench

MySQL Workbench is a graphical tool for working with MySQL servers and databases. MySQL Workbench fully supports MySQL server versions 5.6 and higher. It is also

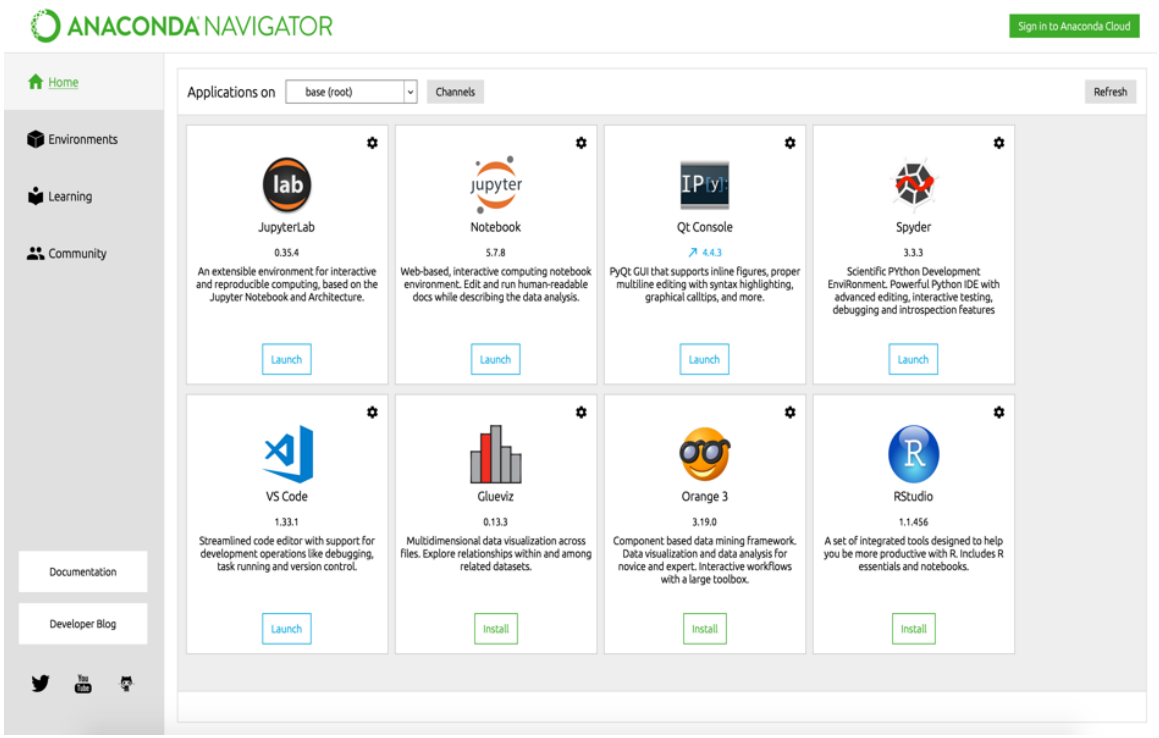

Figure 5.2: Anaconda Navigator GUI.

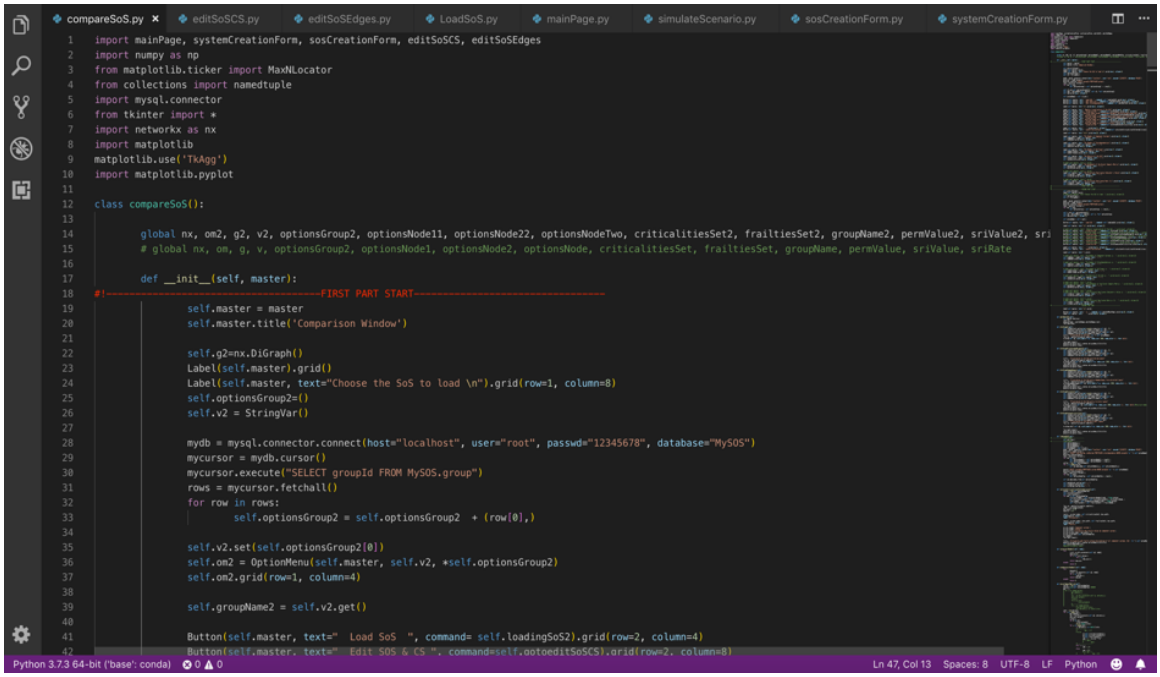

Figure 5.3: VS Code GUI.

compatible with older MySQL server 5.x versions, except in certain situations (like displaying the process list) due to changed system tables. It does not support MySQL server versions 4.x.

MySQL Workbench functionality covers five main topics: SQL Development, Data Modeling, Server Administration, Data Migration, and MySQL Enterprise Support. See Figure 5.4.

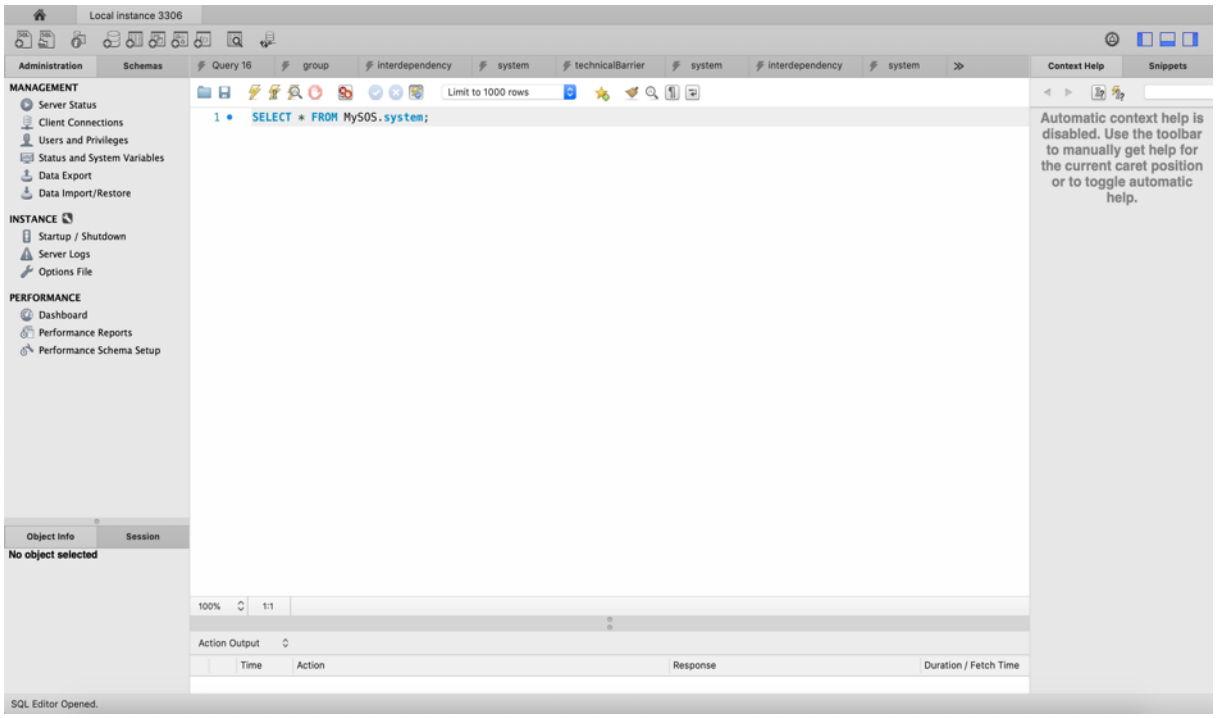

Figure 5.4: MySQL Workbench GUI.

In this study, MySQL Workbench is used in order to create the database based on the class diagram detailed in the previously presented chapter. It provides an easy to use GUI and enables the creation and management of connections to database servers.

MySQL Workbench provides the capability to execute SQL queries on the database connections using the built-in SQL Editor. It enables you to create models of your database schema graphically.

Besides, it includes a Tables Editor that offers facilities to edit Tables, Columns, Indexes, Triggers, Partitioning, Options, Inserts and Privileges, Routines and Views. It also provides the ability to supervise server instances.

5.4 Application to Real-Based Case Studies

In this section, an application of the approach presented in the previous chapter is conducted to two different case studies from the French economic infrastructure. They are inspired by reality and represent two segments from different industries.

One represents a segment of the perfume industry. The second represents a segment of the wood industry. Each case is approached as an independent SoS that is given a topology that accounts for the static representation of its components and the manner they interact and cooperate. The idea is to focus on the component's interface, where data, services and quantities are exchanged through functional relationships.

CS represent companies and arrows represent the workflow pathways and the relations between the CS. For confidentiality reasons, only some areas of the economic infrastructure will be covered. Further information about the economic infrastructure, companies, their names, their locations, etc. will not be provided.

Accordingly, the economic infrastructure insinuates the internal facilities of a country that ease business activity, such as communication, transportation, distribution networks and markets Ed-daoui et al. (2018c).

The application of the approach to both SoS in order to assess their structural resilience will be mixed with the implementation of the model detailed in the previous chapter. The idea is to design a prototype for structural resilience assessment calculations and not to create a standard for the creation of SoS.

In order to be able to calculate the resilience of SoS (in this case the case studies) via the prototype, some steps should be followed. A presentation of each step, starting from the SoS creation to the calculation of the structural resilience of each SoS, will be given through each case study.

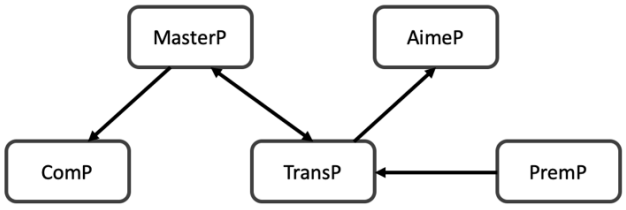

Figure 5.5: First case study: the segment of the perfume industry.

Macroeconomics are not considered in the following. However, it is possible to

prove that the companies that will be presented are actually interacting with each other. An impact on one of them influences all of them but not with the same impact. The idea of this work is to assess the impact of component's failures, caused by the disturbances or other, on the rest of the CS forming the SoS.

5.4.1 The SoS Creation

Figure 5.5 illustrates the perfume industry segment case study. It includes five anonymous companies represented by five CS (AimeP, ComP, MasterP, PremP and TransP). Each one is in a different sector of activity.

Figure 5.6 illustrates the perfume industry segment case study. It also includes five anonymous companies represented by five CS (AimeW, ComW, MasterW, PremW and TransW). Each one is in a different sector of activity.

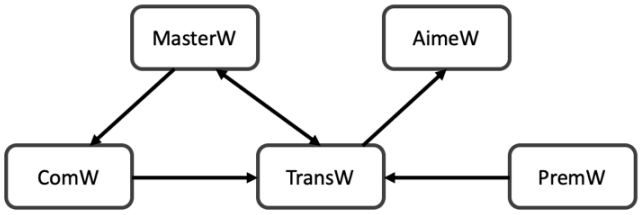

Figure 5.6: Second case study: the segment of the wood industry.

Table 5.1 illustrates each one of the components. There are five different activities present in this region: Retail Distribution, Communication, Manufacturing, Feedstock, Logistics.

First case study companies	**Second case study companies**	**Activity sector**
AimeP	AimeW	***Retail & Distribution***
ComP	ComW	***Communication***
MasterP	MasterW	***Manufacturing***
PermP	PermW	***Feedstock supplier***
TransP	TransW	***Logistics Supplier***

Table 5.1:: CS activity sectors.

Using the designed prototype, the user is able to create SoS. To do so, two information regarding the SoS need to be given. The first one is the SoS identifier and the represented region. There is no need for any quantitative information regarding CS amid the SoS as the idea is to emphasize the SoS openness. Therefore, the CS can join or leave the SoS while the latter remains viable.

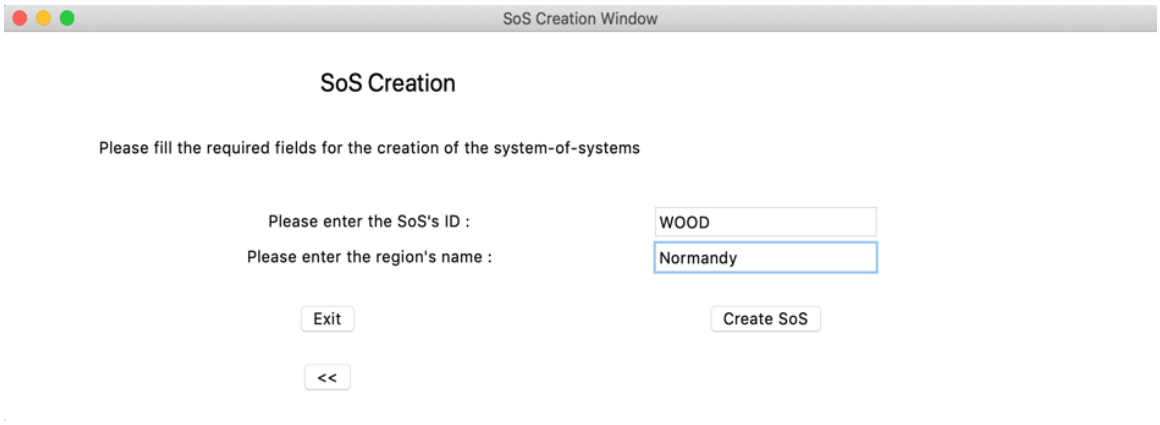

Figure 5.7: The SoS creation's GUI.

Figure 5.7 represents the graphical interface for SoS creation. In this case, two SoS should be created: WOOD and PERFUME. With the first one representing the segment of the wood industry, while the second representing the segment of the perfume industry.

After clicking on the button "Create SoS", if the entered information is valid, it will be stored in a database, and the user will be directly redirected to the CS creation GUI.

In addition, all the entered information is checked and the entered information could be valid or invalid depending on the established constraints.

5.4.2 The CS Creation

When the SoS creation goes well, the CS should also be created and affected to their containing SoS. Figure 5.8 illustrates the CS creation GUI.

The creation of CS requires providing the CS' identifiers and names. It is also important to specify the SoS that will include the CS. For both SoS and CS creations, some constraints need to be considered in the process so as to avoid data redundancy in the database. As an example: the same identifier cannot be assigned to two different CS.

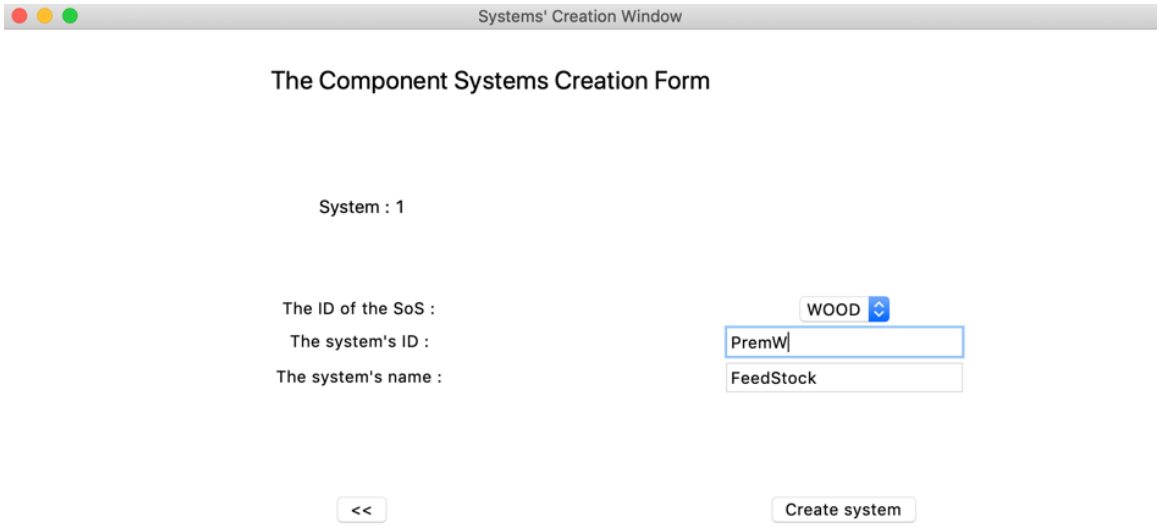

Figure 5.8: CS creation's GUI.

The process of CS creation is iterative. The user keeps entering information concerning CS until the desired amount of CS is achieved. In addition, all the entered information is checked and the entered information could be valid or invalid depending on the established constraints. If the entered information is valid, it will be stored in a database.

In this case, the CS to be entered are:

- AimeP, ComP, MasterP, PermP, TransP within PERFUME SoS.
- AimeW, ComW, MasterW, PermW, TransW withinWOOD SoS.

5.4.3 Interdependencies Establishment

After the creation of the two SoS and their CS, the interdependencies linking the CS and illustrating the workflow pathways are created. They are crucial for the evaluation of structural resilience.

This operation starts by loading the desired SoS. Then, the user chooses the CS to link by interdependencies. The creation of interdependencies is correlated to their storage in the database.

As the interdependencies are represented by arrows, it is important to note that "CS 1" represents the tail of the interdependency and "CS 2" its head. See Figure

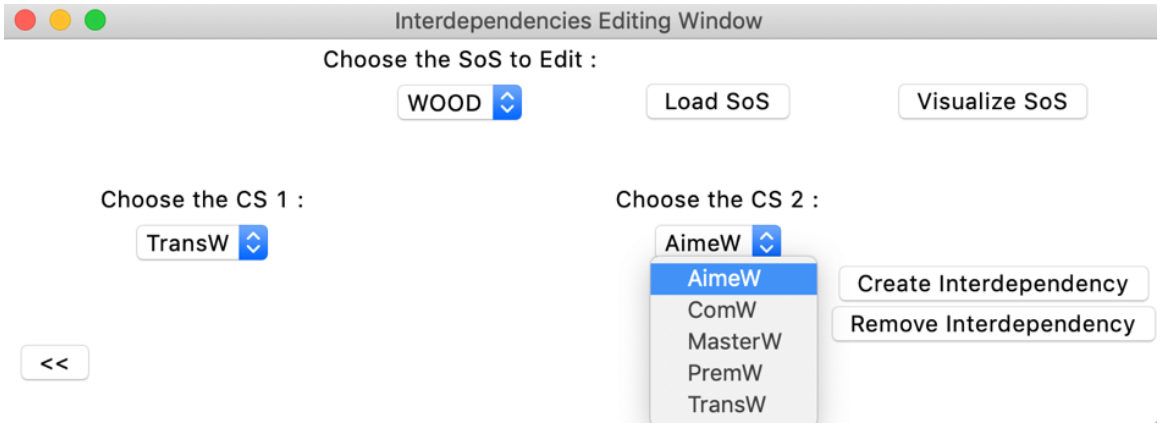

Figure 5.9: Interdependencies creation GUI.

5.9.

It is also possible to remove an interdependency linking two CS. The interdependencies removal is also done with respect to workflow pathways, with "CS 1" representing the tail of the interdependency and "CS 2" its head.

A visualization of the SoS can also be effectuated, preferably when the interdependencies are established by clicking on the button "Visualize SoS".

5.4.4 SoS Loading and Calculations Launching

Now both SoS are fully created. The CS and interdependencies are also included. Thus, stored SoS can also be visualized. There are five visualization options:

- Regular visualization, see Figure 5.10
- Positioning CS using the Fruchterman-Reingold Force-Directed algorithm, see Figure 5.11
- Positioning CS using Kamada-Kawai Path-Length Cost-Function, see Figure 5.12
- Positioning CS on a circle, see Figure 5.13
- Positioning CS in concentric circles, see Figure 5.14

The illustration of SoS also generates information regarding the SoS, such as the number of CS included within the SoS, the number of interdependencies, the number of selfloops and the density of the SoS.

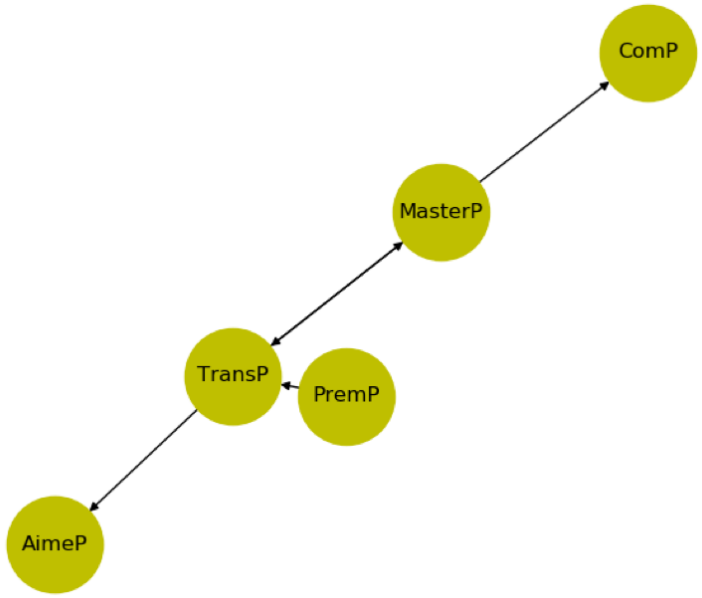

Figure 5.10: Regular illustration of the PERFUME SoS.

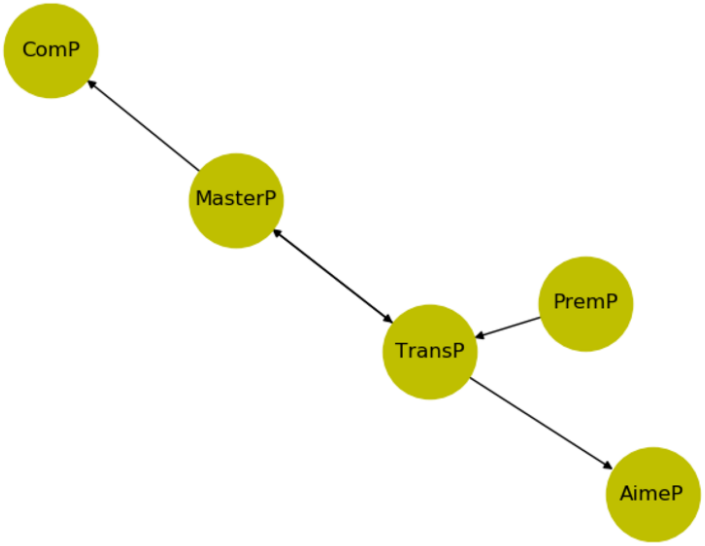

Figure 5.11: Illustration of the PERFUME SoS using Fruchterman-Reingold Force-Directed algorithm.

This information is the result of using some methods from the NetworkX package. At this stage, the SoS is considered as a directed graph. All the methods are applied to it as a directed graph.

Therefore, the loaded SoS can be subject to the structural resilience calculations.

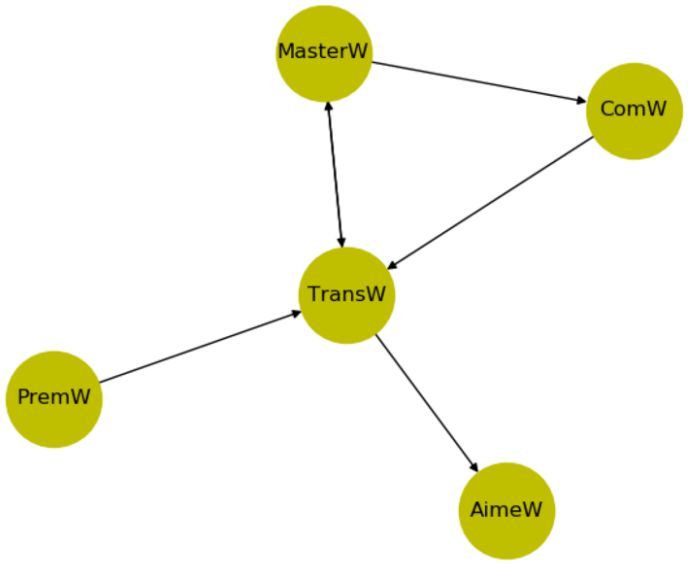

Figure 5.12: Illustration of the WOOD SoS using Kamada-Kawai Path-Length Cost-Function.

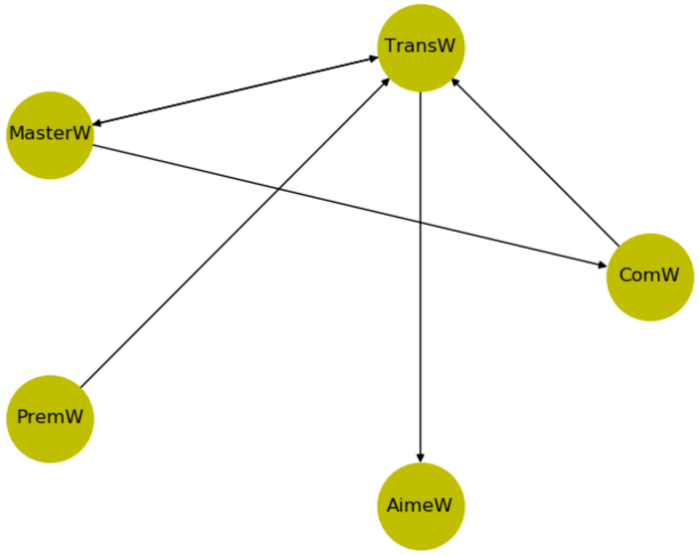

Figure 5.13: Illustration of the WOOD SoS on a circle.

An application is done to the wood industry segment represented by WOOD SoS.

Figure 5.16 illustrates the criticality and frailty measures distribution across the studied WOOD SoS. The CS 'AimeW' is the most influenced CS by the upstream workflow followed by 'ComW', 'MasterW', 'TransW', While 'PremW' is the CS with no upstream workflow which explains the value of its frailty.

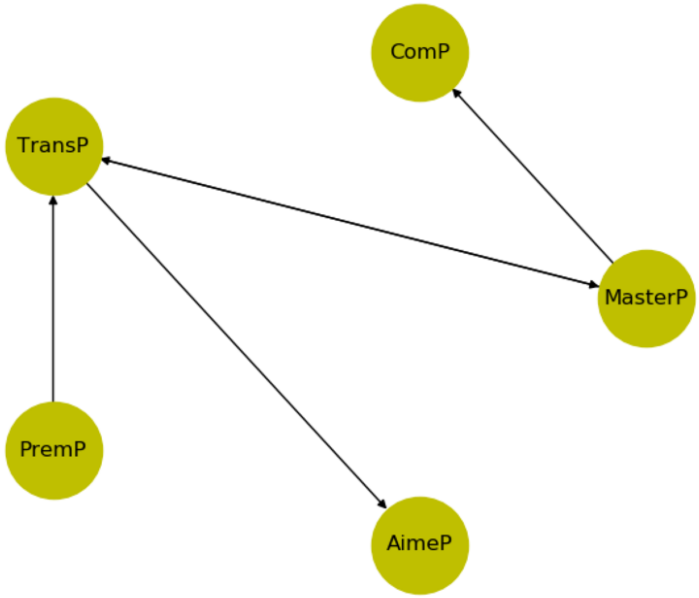

Figure 5.14: Illustration of the WOOD SoS in concentric circles.

On the other hand, 'PremW' is the most influencing CS, followed by 'ComW', 'MasterW', 'TransW', while 'AimeW' is the CS with no downstream workflow. This explains the value of its criticality which is equal to '0'.

Figure 5.17 illustrates the values of the direct impact of each CS on the rest of components amid the studied SoS using the criticality and frailty values. The colors are used in order to ease the results lecture. They are also useful in comparisons.

The calculations generate some results on the graphical interface as it is illustrated in Figure 5.15. They include the permanent of the presented matrix, the structural resilience indicator value and rate are illustrated on the SoS loading and calculations launching GUI.

5.4.5 SoS Comparison

There is also a possibility to compare the structural resilience of two SoS. This is similar to the previous process, besides, it is done through the previously presented operations. The only difference between this GUI and the SoS loading and calculations launching is that two SoS can be loaded and not only one, which provides the possibility to compare.

Figure 5.18 illustrates the GUI of the SoS comparison operation. Both PER-

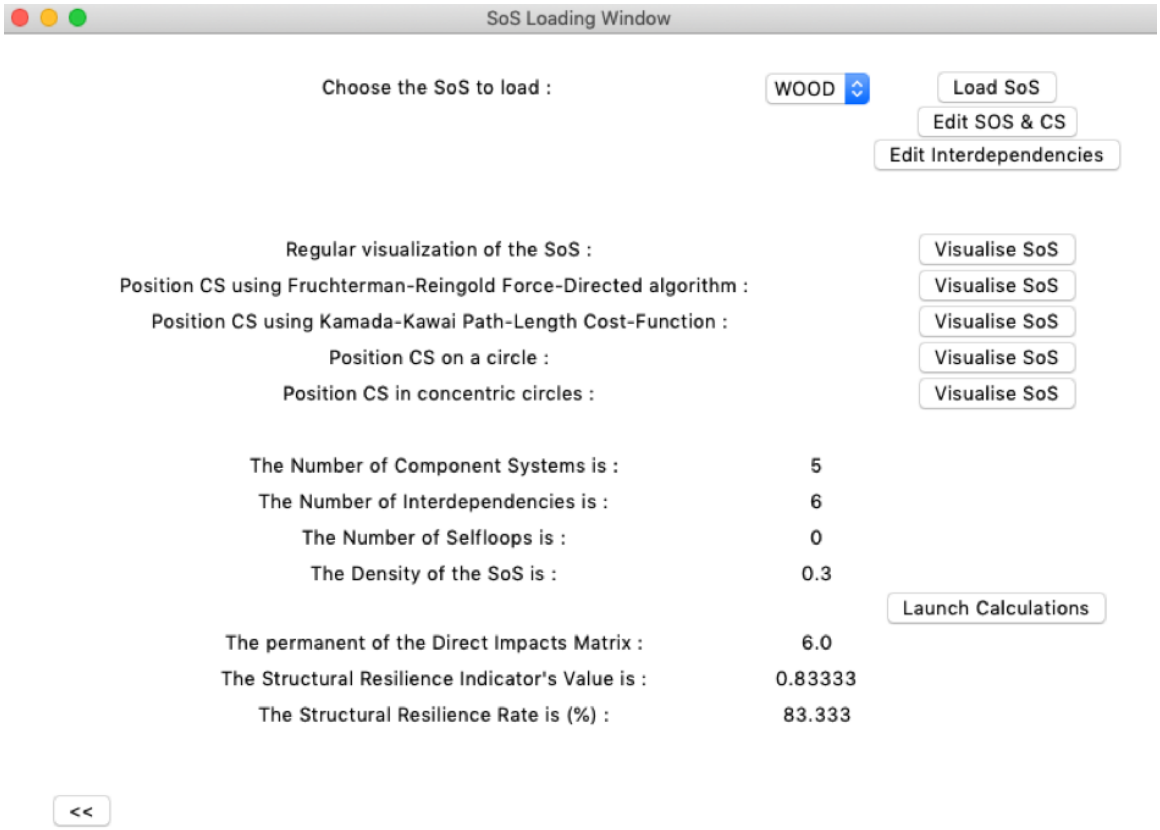

Figure 5.15: WOOD SoS loading and calculations launching GUI.

FUME and WOOD SoS are loaded in order to be compared. As it is noticeable on the figure, the same operations are applicable to both SoS. Both SoS can be visualized through the same options (Regular visualization, using Fruchterman-Reingold Force-Directed algorithm, using Kamada-Kawai Path-Length Cost-Function, positioning CS on a circle and positioning CS in concentric circles).

It is also possible to illustrate the number of CS, interdependencies and selfloops in addition to the density of the SoS perceived as a directed graph of both SoS. As presented in Figure 5.18, both SoS have the same quantity of CS (5), however, WOOD SoS has more interdependencies (6) compared to PERFUME SoS (5). Consequently, this affects the densities of both SoS.

Figure 5.19 presents the results of criticality and frailty calculations for both SoS. The results at the top concerns PERFUME SoS results, while, the results at the bottom are related to WOOD SoS.

It is noticeable that the PremW and PremP are the most critical CS within, respectively, WOOD and PERFUME SoS with the highest criticality rates compared

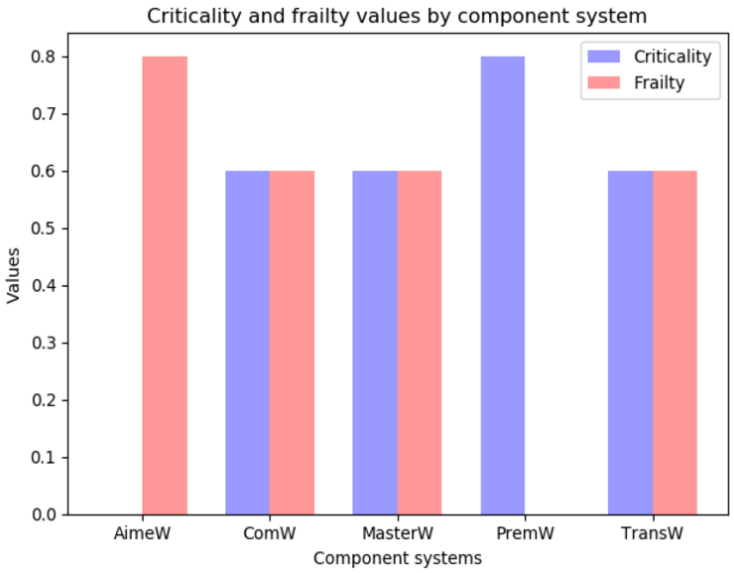

Figure 5.16: Criticality and frailty values distribution by CS.

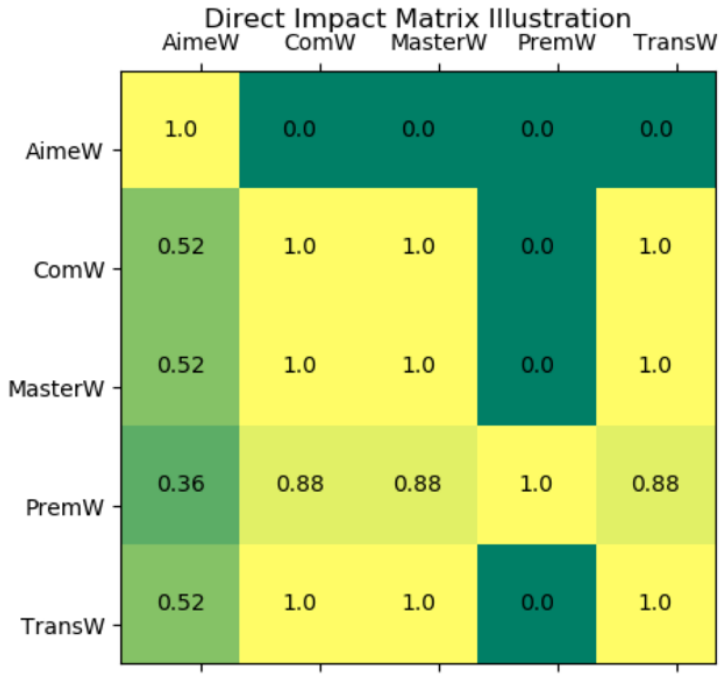

Figure 5.17: Direct impacts matrix.

to the rest of components within their SoS.

From a structural standpoint, the companies in the feedstock activity sector are, generally, the most influencing companies in both industries.

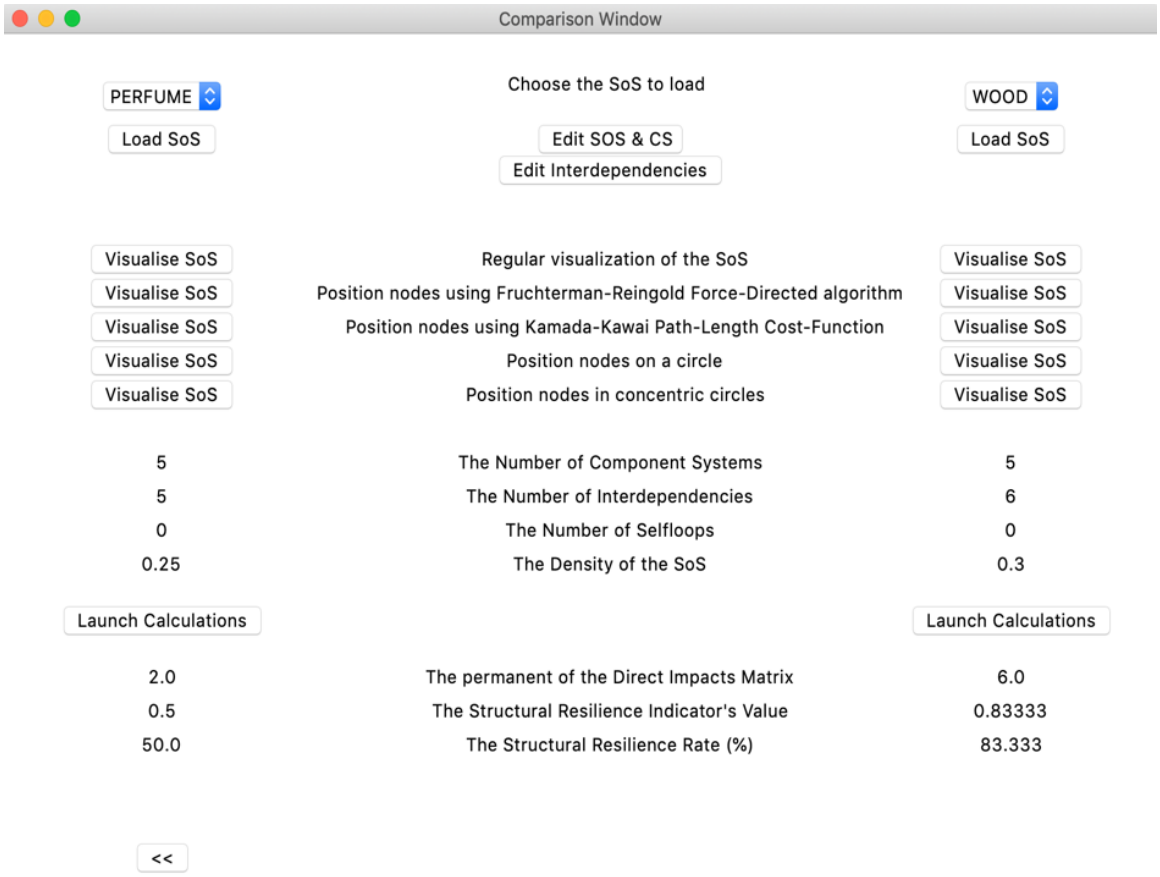

Figure 5.18: SoS comparison GUI.

On the other hand, the AimeW in WOOD SoS in addition to AimeP and ComP are the most influenced CS in their SoS. They are the CS with the highest frailty rates compared to the rest of components within their SoS.

Accordingly, the companies in retail distribution are, generally, the most vulnerable companies in both industries. In PERFUME SoS, ComP is as vulnerable as AimeP with the same frailty rates.

In both SoS, some companies have the same frailty and criticality values, this concerns MasterP and TransP in PERFUME SoS, in addition to MasterW and TransW in WOOD SoS. This is due to their positions with respect to the structural composition of the SoS.

Figure 5.20 presents the results of direct impacts calculations in addition to their mapping on the direct impact matrix. The results at the top concern PERFUME SoS results, while, the results at the bottom are related to WOOD SoS.

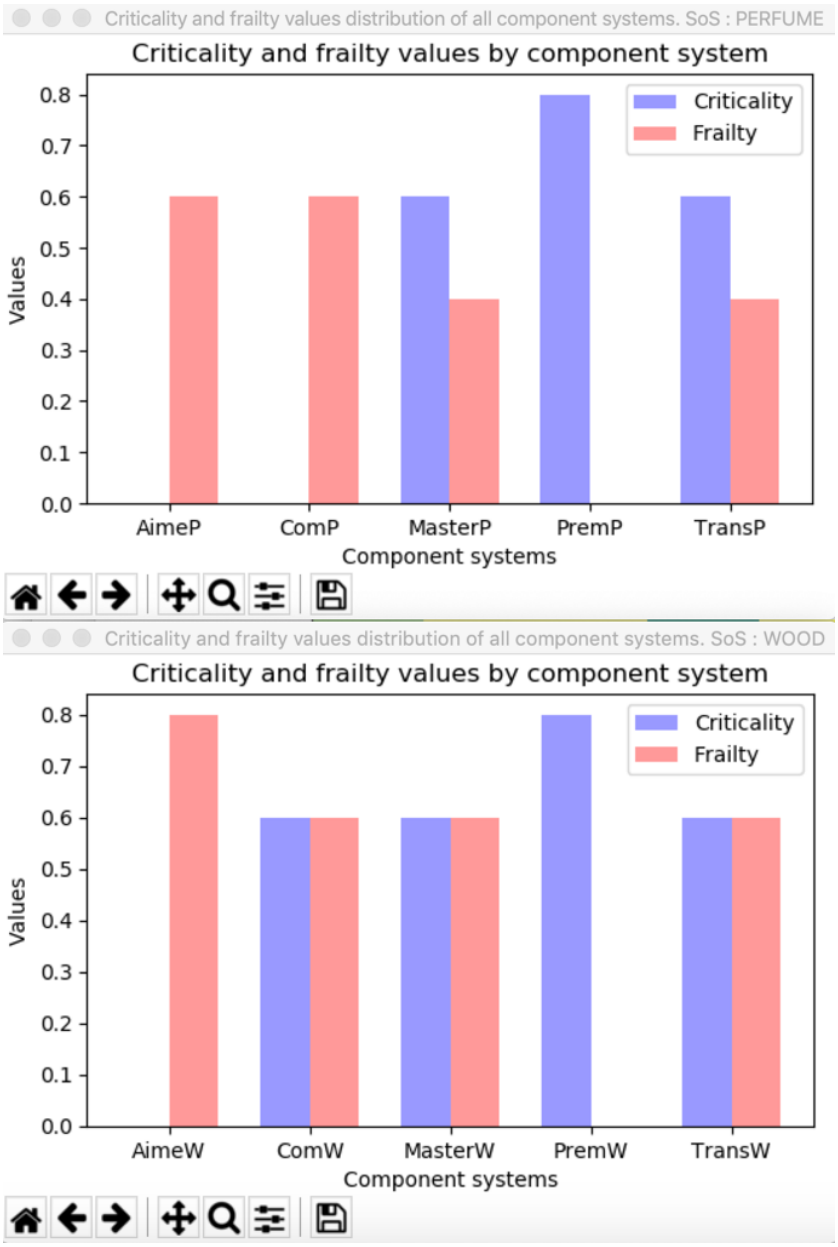

Figure 5.19: Criticality and frailty calculations by CS. Calculations of PERFUME SoS are at the top. Calculations of WOOD SoS are at the bottom.

The values vary between 0 and 1. The differentiation between values is done using colors. The colors help to easily read the matrices.

It is noticeable that the PERFUME matrix has more zeros than the WOOD's. This explains the difference in the values of the structural resilience values and rates.

Based on the proposed calculations, the more the direct impact values approach

Figure 5.20: Direct impacts calculations by CS. Calculations of PERFUME SoS are at the top. Calculations of WOOD SoS are at the bottom.

zero the less the SoS is resilient. And vice versa, the more they approach one the more the SoS is resilient.

Correspondingly, a SoS structure is resilient if it has no zeros in it. The ideal is to have a matrix of ones. This way the structural resilience value will approach 1 and the structural resilience rate will be the closest to 100%.

Eventually, SoS comparison is useful when the user tries to make changes in the SoS, so it loads both SoS and evaluates their structural resilience, and at the end, results are generated which help to know which one is more resilient.

Another utility is the amelioration of the SoS. A comparison of different scenarios can help in choosing the best structural composition of CS. With the use of the proposed resilience indicators, the structural involvement is done with pertinence. As the frail zones within the SoS are swiftly located.

The zone here insinuates places within the SoS. It can embrace only one CS as it can include many. Besides, the direct impact matrix is also useful in the localization of weak and strong zones.

A redirection to SoS, CS, or interdependencies editing can be effectuated by clicking on the button made for this purpose.

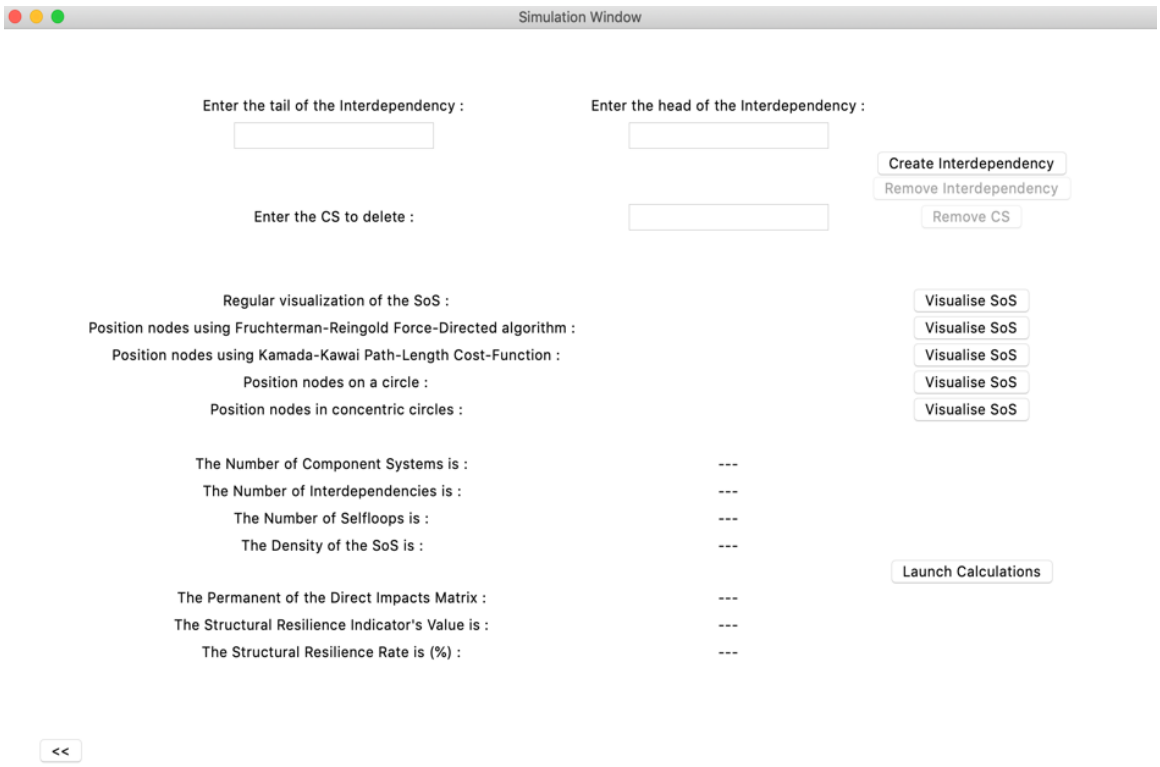

Figure 5.21: Scenario simulation GUI.

5.4.6 SoS Simulation

Another option for SoS amelioration resides in the simulation of the SoS. It helps to create SoS and apply all the calculations and visualization operations on it, but without storing it. And this is the only difference. This can be used for tests and SoS simulations.

The GUI of the scenario simulation includes two entries for the simultaneous creation of the CS and the linking interdependencies. Interdependencies and CS removals can be effectuated. Besides, the visualization options and calculations can also be launched.

5.5 Loops and Structural Resilience Enhancement

A loop is a closed succession of a minimum of three CS. The main characteristic is that the workflow pathways within the loop should respect the same orientation. Figure 5.22 illustrates the differences between loops and ordinary interdependencies networks.

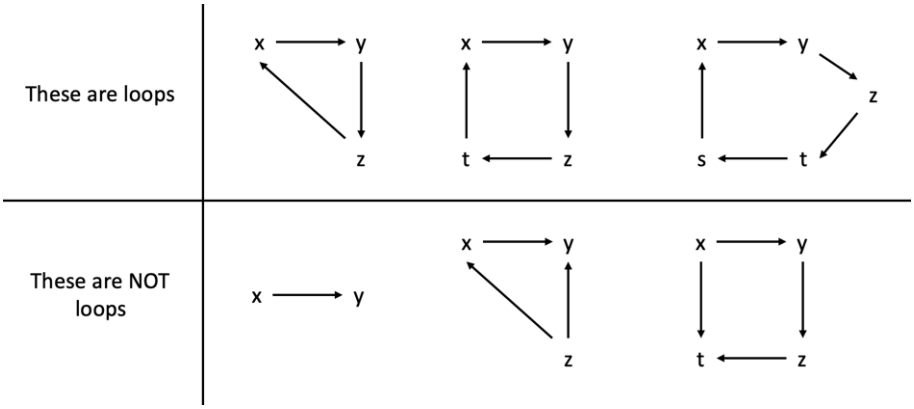

Figure 5.22: Loops vs ordinary interdependencies.

Back to the first case studies, it is noticeable that in the WOOD SoS there is a lop composed of three CS: MasterW, ComW and TransW. Contrarily to the PERFUME SoS, no loops can be detected.

This triggers an important question: "is it just the interdependency between two more CS that enhanced the structural resilience? Or the loop formation that is responsible for the evolvement?"

If we compare PERFUME and WOOD SoS, there is only one interdependency

that makes the difference. So in order to verify what really has an impact on the structural resilience enhancement, a simulation of a scenario is done.

Figure 5.23 illustrates the simulated SoS. It has the same quantity of CS like the previous ones. The structural composition of the WOOD SoS is also conserved. However, the interdependency between TransX and ComX is reversed compared to the one in WOOD SoS. Therefore, criticality and frailty calculations will change. See Figure 5.24.

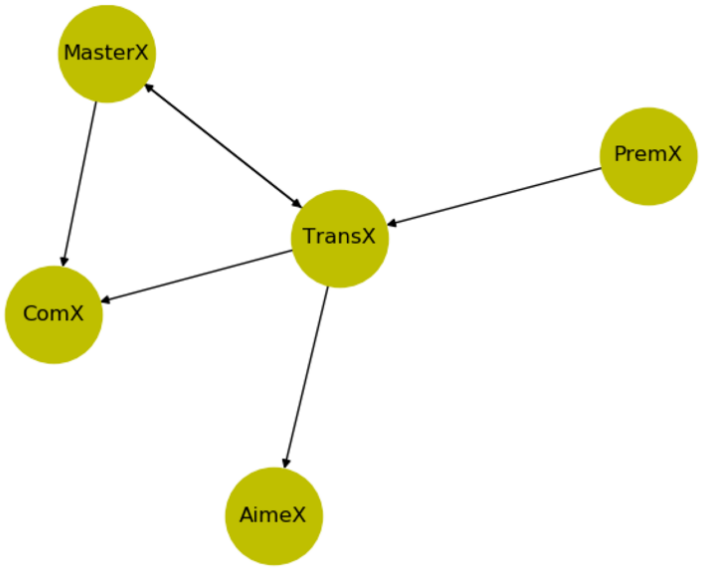

Figure 5.23: Illustration of the simulated SoS.

As we can see, the structural resilience rate and rate have decreased considerably (from 83,33% to 50%). This means that the structural resilience rate can considerably decrease for the WOOD SoS. If we just change the orientation of the workflow pathway between TransW and ComW.

This confirms that there could be a relation between loops and structural resilience enhancement through the proposed approaches.

5.6 Conclusions

This chapter describes an attempt to answer to the concerns related to regional resilience, as in the literature, less attention is given to structures, interactions and workflow pathways within the spatial object in the development of resilience factors Östh et al. (2015), Caschili et al. (2015). Therefore, a prototype is designed to the

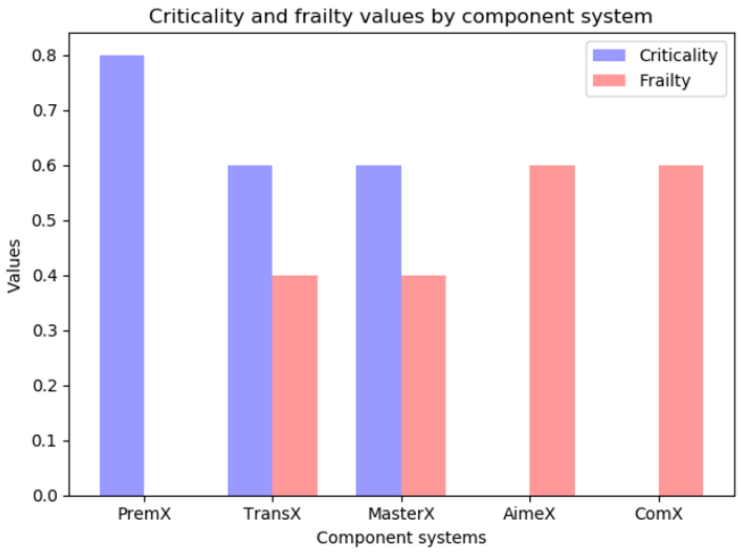

Figure 5.24: Criticality and frailty calculations by CS.

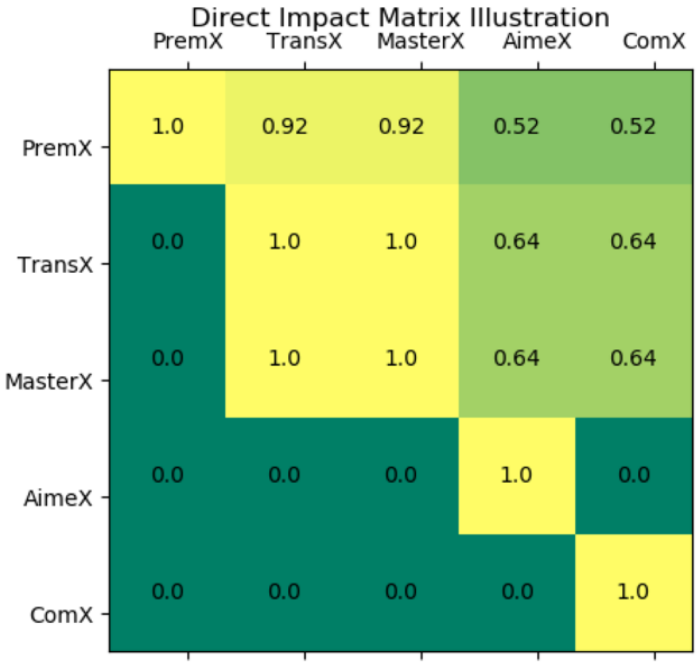

Figure 5.25: Direct impacts calculations by CS.

structural resilience assessment of regions with consideration to the embraced workflow pathways within the spatial object.

The approach is based on the engineering aspect and aims to assess the structural

The Permanent of the Direct Impacts Matrix :	2.0
The Structural Resilience Indicator's Value is :	0.5
The Structural Resilience Rate is (%) :	50.0

Figure 5.26: Permanent of the direct impacts, structural resilience value and rate of the simulated SoS.

resilience of economic infrastructures amid a region. It may also be extended to include the ecological and social aspects, as long as they can also be approached as a SoS. A global SoS embracing different aspects is an interesting potentiality.

The combination of the resilience concept with the spatial object aims to assess and measure the regional development and evolution. It also helps to anticipate and evaluate the impacts of threats targeting an area to elaborate plans and take actions to mitigate their impacts. This combination also takes into account the region's inner behaviors, culture and policy contribution Foster (2007), Christopherson et al. (2010), Dawley et al. (2010), Iordan et al. (2015), Shaw and Maythorne (2013).

General Conclusion & Future Works

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General Conclusion

SoS have received extensive attention in the last years. However, despite the existing initiatives, the theory is not completely established yet and needs more focus as the research community seems to remain struggling with the concept.

One of the commonly consented definitions of SoS is that it represents a synergy of large-scale, heterogeneous, autonomous and interdependent CS which themselves were not conceived to cooperate. These CS operate autonomously but in mutual interaction so as to achieve a common goal that exceeds the sum of the parts.

SoS are different from systems as classically understood as they are characterized by particular systemic and functional properties. In addition, they can be classified according to the way they are managed as well as their ability to adapt to changes.

They tolerate the integration and segregation of heterogeneous CS which triggers the need for standards. They are also needed to cope with the requirements for globalization in addition to the growth of information and technologies.

With the increasing complexity and multi-dimensional structures of CS, in addition to the growing levels of uncertainties and risks, further development is needed in some aspects such as risks management, structural analysis, monitoring, resilience quantification and their influence on SoS reliability.

Lately, expectation of SoS largely exceeded just to be operational. They also need to be reliable, to preserve the same performance, to complete the required functions and most importantly to be capable of anticipating as many defects as possible.

The relationship with resilience is among the numerous approaches to tackle reliability in the SoS context. Resilience is defined as the ability of systems to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time, composite costs and risks.

In this thesis, two complementary approaches are proposed in an attempt to analyze SoS structural resilience. The first one is related to extensibility which is a specific characteristic of SoS as they are in continuous evolvement and change. A major focus is to evaluate SoS structural resilience with regards to its dynamic aspect and through interoperability assessment. On the other hand, a consideration of the SoS structure and inner workflow pathways represents the second approach. This perspective leads to structural resilience assessment through a set of indicators.

Both proposed approaches are deterministic and can be used to evaluate the current state of a SoS structure or to anticipate its resilience in future scenarios.

The combination of these approaches helps to have a futurist perspective towards the potential risks threatening the SoS and their impacts as well as CS influence and frailty on/to the SoS overall performance and process continuity. This helps to be cognizant of the rate of the CS survivability after failures occurrence.

In the presented work, the strength of the correlation between resilience and reliability is leveraged. The aim is to emphasize the mutual correspondence between the two concepts. Fundamentally, resilience evaluation and assessment imply the implicit evaluation and assessment of reliability.

Furthermore, a prototype is designed in order to process the structural resilience assessment. Considering spatial objects, it has been used to conduct experiments on real-based industrial infrastructures approached as SoS.

The combination of the resilience concept with the spatial object aims to assess and measure the regional development. It also helps to anticipate and evaluate the impacts of threats targeting an area to elaborate plans and take actions to mitigate their impacts. This combination also takes into account the region's inner behaviors, culture and policy contribution.

Future Works

Furthermore, this work has the potential to be extended to a real-time methodology for calculating influence and locating impactful CS as the structure of SoS evolves due to its dynamics. The following points also represent potential extensions to the conducted work.

Failure Impact, Susceptibility and Structural Resilience

The inclusion of failure impact and susceptibility metrics, detailed in the fourth chapter, in the calculation of the direct impacts and the structural resilience indicator is one of the potential extensions. These metrics are the continuation of the criticality and frailty metrics in a context where a SoS is distributed into groups of CS.

In terms of calculations, the difference between the distribution and non-distribution of SoS into groups of CS is that in the first case, the CS influence (or vulnerability) on (or to) the SoS inner process are calculated through the failure impact and susceptibility calculations, while in the second case, the calculations are done using criticality and vulnerability metrics.

The failure impact value is obtained by multiplying its criticality by the criticality of the region embracing it Ed-daoui et al. (2018c). On the other hand, the susceptibility of a CS inside a SoS is obtained by the multiplication of its frailty by the frailty of the region embracing it.

Groups criticality (or frailty) values are calculated following the same tactic that has been adopted to calculate each CS criticality (or frailty) on the rest of CS within the same group, with consideration of itself. This means that in addition to the other groups, the group in question joins his criticality (or frailty) set.

Emergence Controllability

In the SoS context, emergence has always been related to unpredictable and unexpected behaviors that occur when there is a will to give up control and let the system govern itself as much as possible Johnson (2002). They arise from the cumulative actions and interactions of the CS amid the SoS and can have a positive or negative effect.

In the best case, emergences will provide unanticipated benefits to the SoS. While in the worst cases, emergent properties can utterly destroy the SoS capabilities. Therefore, in order to make SoS self-governance reliable, emergences must be controlled, even if it is still difficult to identify emergent phenomena using simulations and to expect them through analysis. Until now, they can only be explained after they are recognized and studied.

Emergence controllability offers an interesting expansion to the proposed work. Its inclusion can be used to assess and mitigate the impact of potential negative emergences. This helps to conserve the SoS viability and to develop recovery strategies in case of occurrence.

Graph Theory

Graph theory can be an interesting development of the detailed work. Graphs can be used to illustrate the structure of the SoS and to model the relations, interdependencies and processes amid the SoS. Furthermore, it could also be useful for resilience assessment. In appendices, a thought of using graph theory in SoS modeling and assessment is detailed.

Chapter 6

Résumé Détaillé de la Thèse en Français

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6.1 Introduction

Récemment, dans le domaine de l'ingénierie, les chercheurs s'accorde de plus en plus à dire que le concept de SdS (système de systèmes) est une solution efficace pour mettre en oeuvre et analyser des systèmes, dits SC (systèmes composants), qui sont à la fois complexes, autonomes, hétérogènes, de grande envergure et qui fonctionnent collectivement Abel and Sukkarieh (2006).

L'une des définitions communément admises est qu'un SdS représente une synergie de SC qui n'ont pas été conçus pour coopérer. Ces SC fonctionnent de manière autonome afin d'atteindre un objectif commun.

L'objectif principal de l'exploitation de ces systèmes est d'obtenir des capacités et des performances supérieures à celles que l'on pourrait obtenir avec un système classique. Le concept de SdS présente une perspective de haut niveau et explique les interactions entre les SC. Cependant, les travaux sur le concept du SdS nécessitent d'être approfondi davantage Jamshidi (2008b), Abbott (2006), Meilich (2006).

Les SdS sont qualitativement et structurellement différents des systèmes traditionnels et ne sont pas seulement une version plus large de la structure hiérarchique Abbott (2006). Il existe de nombreuses propriétés systémiques et fonctionnelles qui les distinguent. De plus, ils peuvent être classés selon leur mode de gestion et de leur capacité d'adaptation aux changements.

Leur complexité résulte de l'intégration de divers SC indépendants, évolutifs et distribués. Ils interagissent entre eux afin d'atteindre un objectif plus élevé qu'il ne serait pas possible d'atteindre individuellement. Cela crée l'un des principaux défis découlant de cette complexité : l'incertitude des comportements.

Ces incertitudes résultent de l'absence de spécifications fixes, en plus de la coalition de nouveaux et anciens SC. L'intégration des SC, qui interagissent pour atteindre l'objectif du SdS, entraîne certains comportements émergents. De plus, même si les propriétés de chaque SC sont données et bien définies, l'ingénierie de l'ensemble du SdS et la prévision de ses propriétés fonctionnelles et non fonctionnelles demeurent des tâches difficiles.

Les SdS ont été le centre d'une grande attention ces dernières années et un nombre croissant de conférences et de revues internationales se sont intéressées à ce sujet, comme "the International Conference on Systems-of-Systems Engineering", "the International Workshop on Software Engineering for Systems-of-Systems", "International Journal of System of Systems Engineering", etc., pour n'en citer que quelques-uns.

La communauté professionnelle a uni ses efforts pour proposer de nouvelles solutions qui permettent une ingénierie et un développement précis de tels systèmes. De plus, les études bibliométriques de You et al. (2014) et Axelsson (2015) montrent un nombre croissant de publications de recherche au fil du temps, ce qui démontre la prise de conscience croissante de l'importance de l'ingénierie des SdS.

Compte tenu de la complexité croissante des structures multidimensionnelles des SC, ainsi que la multiplicité des incertitudes et des risques, il est nécessaire de poursuivre le développement de certains aspects tels que la gestion des risques, l'analyse structurelle, la surveillance, la quantification de la résilience et leur influence sur la fiabilité des SdS.

Les SdS doivent être fiables, conserver les mêmes performances, compléter les fonctions requises et surtout être capables d'anticiper autant de défauts que possible. La relation avec la résilience fait partie des nombreuses approches pour aborder la fiabilité dans le contexte des SdS. La résilience est définie comme la capacité des systèmes à résister à une perturbation majeure selon des paramètres de dégradation acceptables et à se redresser dans un délai et à des coûts raisonnables.

L'évaluation de la fiabilité et de la résilience d'une synergie de SC hétérogènes est donc devenue le point de mire de diverses applications: militaires, aérospatiales, spatiales, manufacturières, systèmes environnementaux, gestion des catastrophes, infrastructures critiques, etc. Jamshidi (2008b), Crossley (2004), Lopez (2006), Wojcik and Hoffman (2006).

6.2 Contexte du Projet

Le présent travail était réalisé dans le cadre du projet européen XTerM (Systèmes Complexes, intelligence Territoriale et Mobilité XTerM (2019)). XTerM a été cofinancé par l'Union Européenne à travers le Fonds Européen de Développement Régional (FEDER) et la Région Normandie. L'opération qui a débuté le 1er octobre 2015 se poursuivra jusqu'au 30 septembre 2019.

Réunissant 14 organismes de recherche issus de 8 institutions (Université du Havre Normandie, Université de Rouen Normandie, INSA Rouen Normandie, Université Caen Normandie, IDIT, NEOMA Business School, ESIGELEC, CESI), ce projet de recherche multidisciplinaire visait à faire progresser les connaissances et à proposer des outils d'aide à la décision dans la gestion du territoire.

XTerM s'est concentré sur le développement d'outils pour la gestion "intelli-

gente" des territoires. "L'intelligence territoriale" est un concept développé en vue de comprendre les territoires et la gestion des multiples interactions qui s'y produisent. La complexité de ces systèmes d'interactions, à l'échelle des individus, des organisations ou à celle des infrastructures, conduit aujourd'hui à repenser les analyses, les diagnostics et les services aux citoyens et aux opérationnels.

Le développement territorial invite les chercheurs et les praticiens à mieux prendre en compte la complexité des systèmes territoriaux. Ces systèmes sont basés sur des réseaux d'interactions qui sont de nature différente et d'échelle variable (au niveau des individus comme des organisations). Les nouvelles technologies, les nouveaux dispositifs de communications, l'économie mondialisée, les enjeux de durabilité ne font qu'accroître le niveau de complexité de ces systèmes territoriaux.

Pour parvenir à comprendre et à maîtriser cette complexité, trois champs d'analyse s'ouvrent entre la modélisation et la gouvernance des territoires:

- l'épistémologie de la complexité des systèmes : il s'agit d'interroger les notions et concepts permettant d'identifier cette complexité des systèmes;
- l'enrichissement des bases de connaissances des différents systèmes caractérisant les territoires sous l'angle de la complexité;
- l'élaboration de modèles et simulations formalisant les réseaux complexes des territoires : réseaux routiers, réseaux énergétiques, réseaux sociaux, réseaux logistiques, etc.

XTerM visait à réunir la communauté de chercheurs et de praticiens, s'intéressant à l'intelligence territoriale et aux enjeux autour de la relation entre complexité, territoire, prospective et aide à la décision.

Les contributions relèvent autant de l'épistémologie, de la constitution de base de connaissances, de l'élaboration de modèles et de simulations que de l'implication et du retour des acteurs des territoires sur ces démarches. Dans cette perspective, XTerM s'est particulièrement axé sur les thématiques suivantes:

- Réseaux complexes
- Espaces d'actions encouragés
- Déplacements et complexité
- Territoires et mobilité durable
- Territoires économiques et industriels

6.2.1 Réseaux Complexes

Les systèmes complexes, notamment en termes de réseaux d'intéractions sont modélisés. L'idée était d'étudier les différentes formes et les modèles stochastiques qui caractérisent la complexité de ces réseaux ainsi qu'à l'impact de ces topologies sur la dynamique des systèmes portés par ces réseaux.

Pour étudier la dynamique des systèmes complexes stochastiques, qui fonctionnent dans l'environnement incertain, des méthodes statistiques sont développées. Les différents réseaux caractéristiques des territoires, traités de manière spatio-temporelle, sont des cas pratiques où l'analyse des boucles systémiques entre topologie et dynamique apporte des éléments de compréhension ou d'aide à la décision pour contrôler certaines évolutions de phénomènes : épidémiologie, resilience des territoires, développement des smart cities, etc.

Les contributions portent sur des approches conceptuelles à la théorie des systèmes complexes, les systèmes stochastiques et leur modélisation, sur la dynamique des réseaux complexes, les processus d'auto-organisation et le contrôle de la dynamique des réseaux.

6.2.2 Espaces d'Actions Encouragées

Le but était d'étudier la mobilité d'un individu et d'un agrégat d'individus, ou encore aux interactions d'un individu et d'un agrégat d'individus avec leur environnement, à travers l'évaluation des processus d'émergence et d'auto-organisation qui sous-tendent leur dynamique.

Les contributions montrent la nature temporaire de ces interactions et en particulier l'aspect non-linéaire de leur dynamique ; c'est-à-dire que la mobilité d'un individu et d'un agrégat d'individus présente une relative sensibilité aux conditions initiales pouvant amener à une réorganisation macroscopique des interactions avec l'environnement.

Ils montrent aussi comment le design d'espaces d'actions encouragées peut perturber, déstabiliser, ou offrir des possibilités d'action (i.e., affordance) et amener à une certaine flexibilité ou au contraire à une forme de résistance des comportements face aux changements de configurations (propriétés) de l'environnement.

6.2.3 Déplacements et Complexité

l'idée était de s'interroger sur la capacité des données générées par les objets connectés à constituer un fondement pour la compréhension des mobilités au sein des territoires. Les résultats des travaux sur ces nouvelles mobilités visibles au travers des objets connectés montrent que les usagers n'investissent pas de manière ubiquiste l'espace urbain, et associent des formes de hotspots à des lieux à fréquentation sporadique, des axes de déplacements préférentiels à d'autres axes de déplacements plus temporaires.

L'observation des résultats révèle généralement une grande variabilité et une complexité des mobilités des usagers dans les espaces urbains et les territoires. Les travaux sur cette thématique présentent l'intérêt et les limites des soft data à renouveler les approches de la mobilité.

Ils montrent, également, comment ces mobilités issues des objets connectés rendent compte à la fois de formes de permanence et d'incertitude sur les lieux fréquentés et l'émergence de concentrations éphémères, en fonction du mode de transport utilisé, du type d'évènement enregistré et en fonction du pas de temps sélectionné.

6.2.4 Territoires et Mobilité Durables

Pour améliorer la durabilité des mobilités sur leur territoire, les décideurs publics ont besoin d'outils permettant de connaître l'occupation et l'utilisation de ce territoire (caractéristiques des populations, voies et modes de déplacement, trajets quotidiens, etc.) et d'appréhender l'impact des dispositifs qui sont à leur disposition (impact sur les modes de déplacements, les trajets, les émissions).

La modélisation du territoire, de ses acteurs, et des incidences de tel ou tel dispositif, peut-elle constituer un outil intéressant à cet égard ? Un certain nombre de collectivités se sont déjà dotées de tels outils de prospective, et d'autres manifestent un intérêt pour pouvoir le faire dans un futur plus ou moins proche. L'idée était de trouver des moyens pour réaliser cette modélisation (collecte de données via nouvelles enquêtes, utilisation de big data, développement de nouveaux modèles, couplage de modèles, renouvellement des approches existantes).

La contributions devaient porter sur la question des indicateurs et des possibles effets sociaux de la réduction du concept de durabilité à ses dimensions environnementales et économiques. Il existe également un besoin de diversification des indicateurs qui soient plus sensibles au volet "social" (santé, exclusion, risque de stigmatisation de certaines catégories de population).

6.2.5 Territoires Économiques et Industriels

L'analyse des enjeux et des transformations des filières industrielles ou logistiques permettent d'observer des évolutions importantes liées à la flexibilité ou à la reconfigurabilité des systèmes. Cela se traduit également par une digitalisation des processus et des transformations des organisations et des modes de pilotage de ces systèmes allant de l'outil de production à la chaine logistique. Outre les changements organisationnels et les évolutions des modes de management, ces évolutions s'appuient sur le développement de l'informatique et des technologies de l'information et de la communication (internet des objets, machines connectées, big data, logiciels de supervision, intelligence artificielle, etc.), associées à l'essor de la robotique (robotique mobile, robotique collaborative etc.) et sur la modélisation, la simulation et l'optimisation de ces systèmes complexes. En l'occurrence, cette thèse s'inscrit dans le cadre de cet axe.

Les travaux menés ont ouvert de nouveaux champs d'applications dans l'inspection ou la surveillance d'équipements et de sites industriels, amenant à repenser les outils industriels et les modes d'organisation associés et à s'intéresser aux processus supply chain, aux processus d'entreprises étendues ou encore de filières tout en intégrant les dimensions humaines et économiques.

6.3 Problématique

L'un des principes fondateurs de la fiabilité est la nécessité d'adopter une approche systémique pour comprendre comment une organisation ou une composition de composants réussit et parfois échoue à gérer des systèmes de plus en plus complexes, surtout dans des contextes où les perturbations et les risques existent. Une approche systémique pour aborder le problème de la fiabilité dans les systèmes complexes exige un changement dans la façon d'étudier, de modéliser et de mesurer les processus opérationnels.

Dans le contexte de la fiabilité, la résilience représente la capacité d'un système à "ajuster son fonctionnement afin qu'il puisse continuer à fonctionner après une perturbation ou un accident majeur" Hollnagel et al. (2006), Cedergren et al. (2018), Patriarca et al. (2018).

Dans le contexte des SdS, la résilience reste difficile à interpréter. Cependant, il s'agit généralement de la capacité d'un système à résister à un événement imprévisible ou à un risque et à se redresser. Elle concerne les conséquences en cas de risques et

d'incertitudes inhérentes.

Comprendre la résilience peut être utile et pratique pour aborder la fiabilité et la sûreté des SdS ainsi qu'à la capacité de leur survie. Les spécialistes considèrent généralement les concepts de fiabilité et de résilience comme étroitement liés. En revanche, il n'existe pas d'études pour appuyer cette croyance. Conséquemment, cette thèse vise à mettre l'accent sur la correspondance mutuelle entre les deux concepts.

Dans la littérature, il y a également un manque perceptible de travaux consacrés à la résilience, l'analyse structurelle ainsi que l'analyse et l'évaluation du niveau d'interopérabilité de ces systèmes. Les approches visant à quantifier les impacts des SC sur la viabilité du système et l'impact du processus dans le SdS sur chacun des SC manquent également de documentation.

6.4 Contributions

Dans cette thèse, la force de la corrélation entre la résilience et la fiabilité est mise à profit. L'objectif est de mettre l'accent sur la correspondance mutuelle entre les deux concepts. L'évaluation de la résilience implique l'évaluation implicite de la fiabilité.

Cette thèse propose des approches déterministes dédiées à l'évaluation de la résilience des SdS par le biais de l'analyse structurelle. En outre, les approches d'analyse structurelle proposées visent à combler l'écart entre les SdS, la résilience et la fiabilité.

La première proposition est liée à l'extensibilité, qui est une caractéristique spécifique des SdS, car ils sont en évolution et en changement continus. L'un des principaux objectifs est d'évaluer la résilience structurelle des SdS, en tenant compte de son aspect dynamique et par le biais de l'évaluation de l'interopérabilité.

La deuxième contribution représente un examen de la structure des SdS et des cheminements internes du flux de travail. Cette perspective conduit à l'évaluation de la résilience structurelle par une séquence de calculs.

Pour tenter de combiner la résilience avec la structure d'un territoire en plus des comportements et flux internes, un prototype est conçu. La combinaison vise à évaluer et à mesurer le développement régional. Il permet également d'anticiper et d'évaluer les impacts des menaces visant une zone afin d'élaborer des plans et de prendre des mesures pour atténuer leurs impacts. Cette combinaison considère implicitement les comportements internes, la culture et l'orientation politique de la région.

6.5 Organisation de la Thèse

Chapitre 1

Ce chapitre constitue l'introduction générale de cette thèse. Il présente le contexte général de l'étude réalisée. Il détaille également le projet européen engolobant cette thèse. Les problèmes de recherche et les principales contributions pour répondre et surmonter ces défis sont exposés. Les publications sont également répertoriés.

Chapitre 2

Même si le but de cette thèse n'est pas une analyse documentaire systémique et complète, une évaluation de certaines approches existantes et pertinentes, qui ont été publiées, est effectuée. L'idée est de se faire une idée de l'état actuel de la résilience des SdS ainsi qu'aux mesures développées et dédiées à l'évaluation et la quantification.

L'extraction des publications s'est faite de façon structurée en utilisant des mots clés appropriés liés aux systèmes de systèmes, l'ingénierie des systèmes de systèmes, la résilience, la fiabilité, la sécurité, l'analyse structurelle, la résilience régionale et la compétitivité régionale, développement régional, évaluation des risques, évaluation de l'interopérabilité, etc. Plusieurs critères d'inclusion et d'exclusion sont utilisés pour sélectionner les études pertinentes.

Les définitions, les propriétés, la taxonomie, les cadres et les normes les plus importants, en plus de l'ingénierie des SdS, sont détaillés dans ce chapitre. Un aperçu chronologique de certaines contributions dans le domaine SoS/SoSE est également présenté. Une description de la fiabilité et de la résilience, dans le contexte des SdS, est également faite dans ce chapitre.

Chapitre 3

Ce chapitre présente une approche dédiée à l'évaluation de la résilience structurelle des SdS par l'évaluation de l'interopérabilité. Elle est liée à l'aspect dynamique des SdS. C'est aussi une réponse à la nécessité croissante d'exploiter de tels systèmes et à l'augmentation rapide des coûts des redressements après des défaillances.

En outre, une classification illustrative des propriétés d'interopérabilité est détaillée. Dans cette taxonomie, l'accent est mis sur certains axes importants de l'analyse et de l'évaluation de la structure des SdS. L'approche proposée repose sur une analyse structurelle et vise à évaluer les interdépendances fonctionnelles entre les systèmes.

Ce processus doit être appliqué, de la même manière, à chaque interdépendance en se basant sur la structure du système global.

Chapitre 4

Ce chapitre tente de répondre aux préoccupations liées à la résilience des SdS par le biais de l'analyse structurelle et la gestion des risques. Les structures des SdS sont modélisées sous la forme de graphes orientés mettant l'accent sur leur aspect statique. Les noeuds représentent les SC ou les capacités qui doivent être acquises. En conséquence, les liens représentent les interdépendances entre les systèmes ou entre les capacités.

Une approche est proposée pour analyser les risques, leurs influences et leurs impacts, ce qui contribue à l'anticipation quantitative de la résilience des SdS. Il s'agit également d'une étape implicite vers l'évaluation et l'amélioration de la fiabilité.

La gestion des risques repose sur deux étapes importantes : une classification des risques qui repose sur leurs natures et leurs sources ainsi qu'un suivi des risques pour les évaluer, analyser et superviser.

L'analyse structurelle commence par l'évaluation des interdépendances fonctionnelles. Vient ensuite, l'estimation de la dépendance de la continuité du processus à l'égard de chaque SC et l'influence de chaque SC sur l'ensemble du processus au sein du SdS, grâce à une séquence de calculs.

Chapitre 5

Ce chapitre résume une tentative de réponse aux préoccupations liées à la résilience régionale. Un prototype est conçu pour combiner la résilience avec la structure des territoires qui inclut les flux interne. La combinaison du concept de résilience avec les territoires vise à évaluer et à mesurer le développement et l'évolution des régions.

Cette combinaison tient également compte des comportements, de la culture et de la contribution politique au sein d'une région. Elle permet d'anticiper et d'évaluer les impacts des menaces visant une zone afin d'élaborer des plans et de prendre des mesures pour atténuer leurs impacts.

L'approche est basée sur l'ingénierie des systèmes et vise à évaluer la résilience structurelle des infrastructures économiques d'une région. Elle peut également être étendue aux aspects écologiques et sociaux, pour autant qu'ils puissent également être abordés en tant que SdS.

6.6 Perspectives

Ce travail a le potentiel d'être étendu à une méthodologie qui permetterait de calculer l'influence et localiser les SC les plus influents, en temps réel, comme la structure des SdS évolue dynamiquement. Les points suivants représentent également des extentions potentielles aux travaux réalisés.

6.6.1 Influence, Susceptibilité et Résilience Structurelle

L'inclusion des notions d'influence et de susceptibilité, détaillées dans le quatrième chapitre, dans le calcul de l'indicateur de résilience structurelle est l'une des extensions possibles. Ces métriques sont la continuation des métriques: "Criticality" (Criticité) et "Frailty" (Fragilité) dans un contexte où un SdS est distribué en groupes.

En termes de calculs, la différence entre la distribution et la non-distribution des SdS en groupes est que dans le premier cas, la résilience structurelles des SdS est évaluée par le calcul des influences et des susceptibilités. Or dans le cas d'un SdS non-distribué en groupes, les calculs sont faits en utilisant les deux métriques: la criticité et la fragilité.

L'influence d'un SC est obtenue en multipliant sa criticité par la criticité du groupe qui l'englobe Ed-daoui et al. (2018c). D'autre part, la susceptibilité d'un SC à l'intérieur d'une SdS est obtenue par la multiplication de sa fragilité par la fragilité du groupe qui l'englobe.

Les valeurs de criticité (ou de fragilité) des groupes sont calculées selon la même méthode que celle qui a été adoptée pour calculer chaque criticité (ou fragilité) d'un SC sur le reste des SC au sein du même groupe, en tenant compte d'elle-même. Cela signifie qu'en plus des autres groupes, le groupe, en question, rejoint son ensemble de criticité (ou de fragilité).

6.6.2 Contrôle des Émergences

Dans le contexte des SdS, l'émergence a toujours été liée aux comportements imprévisibles et inattendus qui surviennent lorsqu'il y a une volonté d'abandonner le contrôle et de laisser le système se gouverner autant que possible Johnson (2002). Les émergences découlent des actions et interactions cumulatives entre les SC au sein de l'ensemble des SdS et peuvent avoir un effet positif ou négatif.

Dans le meilleur des cas, les émergences procureront des avantages imprévus au

SdS. Alors que dans le pire des cas, les propriétés émergentes peuvent complètement détruire les capacités du SoS. Par conséquent, pour fiabiliser l'autogestion des SdS, il faut maîtriser les émergences, même s'il est encore difficile d'identifier les phénomènes émergents à l'aide de simulations ou de les anticiper par des analyses. Jusqu'à présent, elles ne peuvent être expliquées qu'après qu'elles soient reconnues et étudiées.

Le contrôle de l'émergence offre aussi une extension intéressante au travail proposé. Leur combinaison peut être utilisée pour évaluer et atténuer l'impact des émergences négatives. Cela aide à préserver la viabilité des SdS et à élaborer des stratégies de rétablissement en cas d'occurrence.

6.6.3 La Théorie des Graphes

La théorie des graphes peut être un développement intéressant du travail détaillé. Les graphes peuvent être utilisés pour illustrer les structures des SdS et pour modéliser les relations, les interdépendances et les processus au sein des SdS. En outre, il pourrait également être utile pour l'évaluation de la résilience, notamment, moyennant la notion de la connexité.

Appendix A

Graphs & SoS Assessment

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A.1 SoS Assessment through Graph Theory

Graph theory can be a pertinent tool for SoS modelling and assessment. They can perfectly model relations, interdependencies and processes amid the SoS. We believe that graph theory, and especially, connectivity can be important tools that could help in the assessment of SoS structural resilience.

The idea is that when a graph is reduced to quotients and edges linking them, the more the quotients set's cardinal is big, the more the SoS is distributed and there is a risk of isolation/disconnection.

On the other hand, for a more resilient SoS, the number of strongly connected components should be small. Therefore, the SoS will be less distributed and there will be less risk of isolation/disconnection in case of risks occurrence.

Accordingly, the number of the equivalent classes of a graph also impacts the homogeneity of the traffic and processes within the SoS. Therefore, the less there is strongly connected components in a graph, the more the SoS is homogenous and resilient.

A.2 Example of Application

A directed graph is elaborated to represent the studied SoS in order to emphasize the processes and data pathways within the SoS (see Figure A.1). The edges represent the functional interdependencies.

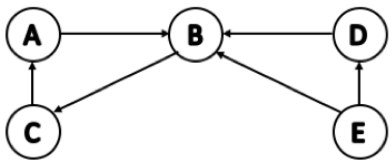

Figure A.1: A directed graph representing an SoS.

The process of resilience assessment through connectivity evaluation can be done through 3 steps:

- The elaboration of the graph with regards to the SoS's structure.
- The calculation of strongly connected components.

- The elaboration of the reduced graph.

In the studied example, there are two strongly connected components with regards to the strong connectivity amid the graph. Given a set E and an equivalence relation R on E, a strongly connected component is defined as a subset $F \subset E$ where its elements are related by R. The strongly connected components of $x \in E$ is defined by:

$$y \in E : yRx$$

In this case, the strongly connected components are:

$$\overline{\mathrm{A}} = A, B, C; \overline{\mathrm{D}} = D; \overline{\mathrm{E}} = E$$

As a result, the first graph can be reduced to the graph in Figure A.2.

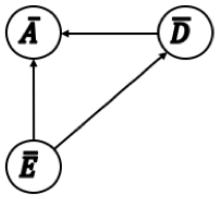

Figure A.2: The reduced graph of the studied system.

A.3 Example Continued

Before getting to the resilience assessment, another graph representing a slightly different SoS is created in order to compare both of them. This will emphasize the role of the proposed approach.

The difference between both graphs (and implicitly both SoS) is that in the second graph we add an edge creating a path from the vertex J to the vertex F, which was not in the first graph. As a result, there is only one strongly connected component:

$$\overline{\mathrm{A}} = A, B, C, D, E$$

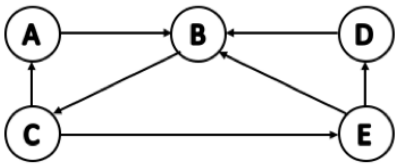

Figure A.3: A directed graph representing the second SoS.

A.4 Discussion

In the first example (Figure 2), the reduced graph includes three strongly connected components, while in the second one, the reduced graph only includes one strongly connected component. Therefore, the structure is more homogeneous.

We see that homogeneity can be an important property for resilient systems and especially SoS, as the CS (represented as vertices) are less exposed to disconnection or isolation in case of risk's occurrence. The idea is in its embryonic stage and further work is needed to develop it.

Appendix B

Adaptive Integration Management

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B.1 The Integration as an Object of Inspection

In a context where systems have the tendency to be complex, heterogeneous and autonomous, handling the integration process while conserving the viability of the performance represents a major challenge Ed-daoui et al. (2018b). Besides, this issue triggers other concerns, such as resource discovery, data routing and interoperability, which place a significant load on the engineers, who have to develop simulation models to support it Kewley et al. (2008), Scholtes et al. (2010).

Integration in a SoS context insinuates, that each system should be able to interact with the rest of CS regardless of their hardware, software characteristics or nature, just after joining the system. In addition, the integration process should be followed by an eventual ability to communicate without compatibility issues and should not negatively influence the performance of the SoS.

There is no standardized mechanism, methodology or framework for SoS integration management. However, there has been an active research community addressing the main topics of interest related to SoS integration process.

In a SoS, CS need to have the ability to communicate with each other without any compatibility issues, which may include operating systems, hardware and so on. Thus, this urges the need for intelligent mechanisms regarding integration management in addition to inherent interoperability analysis to overcome intrinsic issues.

In Jamshidi (2008b), the author says, that a SoS needs to have a common language for communication for all CS. As the absence of a common language implies the effectuation of major efforts in order to integrate systems. Thus, the SoS could not be adaptive.

This leads us to think, that integration should go beyond the physical interactions when it comes to SoS. This idea has been consolidated in Jamshidi (2008b), where three levels of integration are described:

- **Physical integration:** related to physical interfaces, ports and protocols.
- **Functional integration:** refers to systems' compatibility and incompatibility.
- **Semantic integration:** refers to the interpretation given by systems to signals and data transiting within the system

B.2 Integration Challenges and Contribution Outline

Table B.1 depicts the integration challenges for both directed and open SoS. It shows that both share some worries, especially regarding interoperability, compatibility, resource discovery and data routing.

Integration limitations for directed SoS	**Integration limitations for open SoS**
• Interoperability • Compatibility • Resource discovery • Data routing	• Dispersion of objectives • Interoperability • Compatibility • Resource discovery • Data routing

Table B.1:: Integration challenges for directed and open SoS.

However, open SoS have an additional issue which is due to its special structure and hierarchy of objectives. It is due to objectives dispersion. It complicates the integration process because more interactions are needed to cover all dispersed CS.

Besides, the more the open SoS is big, the more it will be complicated to integrate new systems, since a huge amount of interactions will be needed.

Regarding the state-of-the-art, there is a lack of approaches and propositions that addresses the integration management issue in SoS by considering the differences in organization inside the SoS as a foundation.

Hereby, an adaptive integration process to SoS typology is described. Every change in the system's topology triggers an update of all systems' tables. Correspondingly, each integrating system collects information about the topology and creates its own dynamic systems table. It would be judicious to approach the integration process differently, namely depending on the typology since each type has different interaction policies and paradigms. This means, that a different integration process should be adopted in each class of SoS.

B.3 The Integration Process amid Open SoS

The integration process in open SoS requires more interactions than its corresponding in directed SoS. This is due to the dispersion of objectives, which implies the dispersion of CS. This leads to more interactions that are no longer restricted only to CS assigned to the same objective but to all existing ones. The more the SoS is bigger, the more complicated it will be.

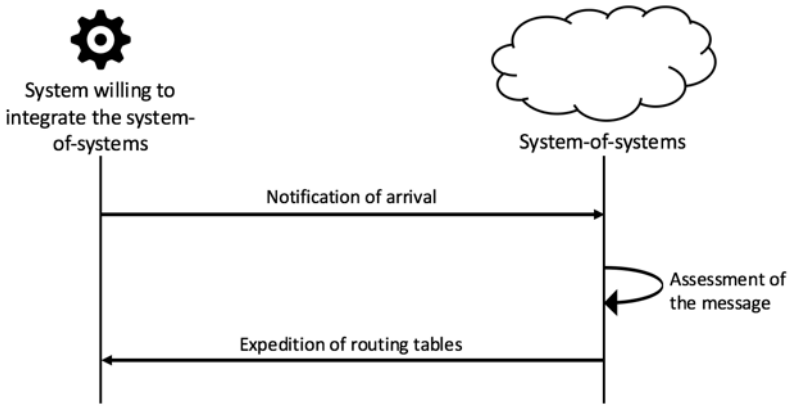

Figure B.1: The initial phase of the integration process in open SoS.

In fact, the integration process includes two key phases.: an initial phase and the veritable inclusion of the system into the SoS.

In fact, the integration process includes two key phases. The first phase serves as a preliminary stage of integration. It prepares the SoS for an eventual veritable integration process. It starts with the transmission of a search message to all CS within the SoS. Then, an assessment of the message takes place. Next, in the case of a successful scenario, CS send back their system's tables which contain information about locations, addresses, data, etc. The process is depicted in Figure B.1.

While the second phase, which embraces the veritable inclusion of the system into the SoS, also includes three stages:

- Table's clone: when the system receives the system's tables from CS, which are normally the same, it duplicates its content and creates the first version of its table, that is similar to what already exists.
- Injection of information in the table: after the replication of the system's tables, the system injects its data and information including its task and assigned

objective in the table. The result is a new table including the new system as well.

- Expedition of the table: as soon as the new system finishes integrating itself in the system's table, it transmits it to all CS, who have already sent him the ancient version of the table.

- Tables update: all systems should eventually replace their tables by the new table.

By following this process, the SoS will have a standardized form of tables. This is helpful because it limits compatibility issues, in addition, it helps the component to have a common vision through the SoS. However, updating tables after a segregation is still a major constraint to this approach.

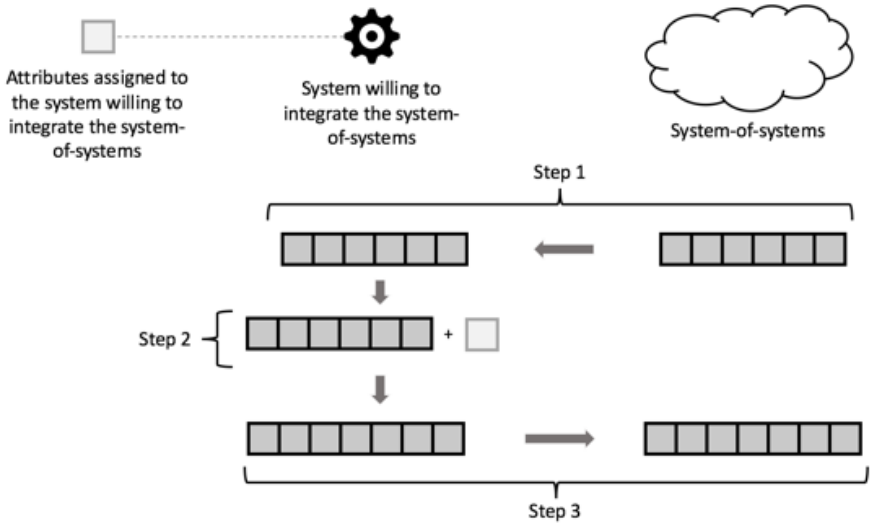

Figure B.2: Illustration of the integration process in open SoS.

Figure B.2 demonstrates the steps of the organization of the system alongside CS in order to achieve a successful integration. "Step 1" represents the transition of systems tables from CS to the new system. This is a common move between both phases of integration. This step also includes the table's clone stage, where the system duplicates the content of the received table (since all tables are identical) and creates the first version of its table that is similar to what already exists.

"Step 2" includes the injection of information in the table stage, which returns a new table that includes the new system's attributes as well. And finally "Step 3" includes the expedition of the table's stage where it transmits the new systems table

to all systems, who have already sent him the ancient version of the table. Eventually, all systems should replace their tables by the new table in an implicit and underlying step, that standardizes the tables through the SoS.

Figure B.3 depicts the integration process for open SoS including all the steps previously explained.

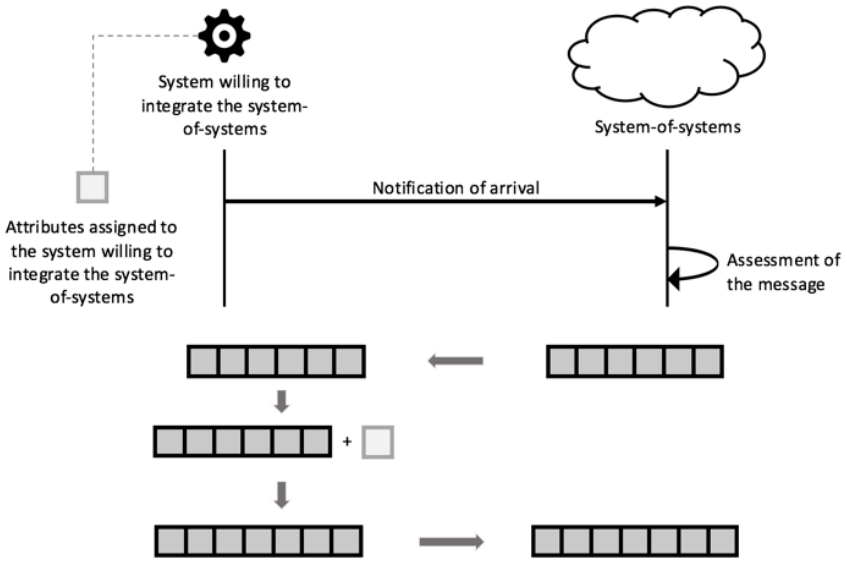

Figure B.3: The complete integration process for open SoS.

Now the question is: why do CS need to have all routes and systems in their tables in open SoS?

In fact, that is due to the non-existence of information centralization and the absence of management. In other words, the system needs to have all systems included in its table for self-directness and self-management purposes.

B.4 The Integration Process amid Directed SoS

The integration in directed SoS context is done through three phases. The first phase, called the selection phase, is about logically isolating the concerned set of CS assigned to the implicated target. Other CS are not affected since they are assigned to other targets.

The second phase, called the initial integration, is about integrating the new system among the set of CS assigned to the implicated target. A specific task is

chosen and assigned to the new CS.

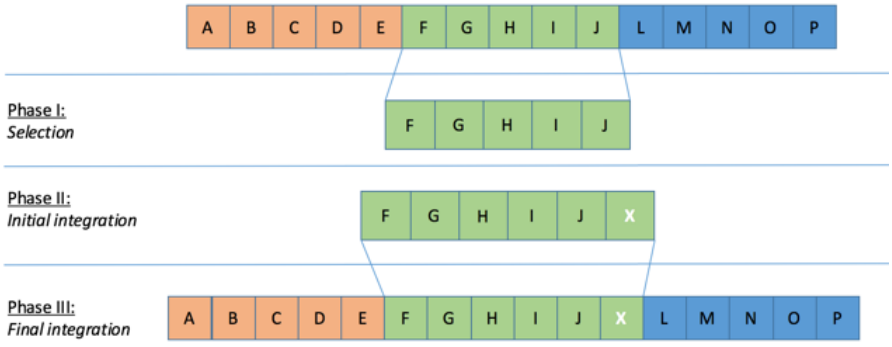

Figure B.4: An example of the integration in directed SoS. Three groups are included and differentiated by colors.

The third and final phase, called final integration, is about reintegrating the set of systems inside the SoS. This step may be implicit, as all systems inside are heterogeneous, autonomous and independent. Besides, the newly integrating system does not need to interoperate with systems assigned to another target in order to accomplish its task.

A system does not communicate with the whole SoS neither during the integration process nor after a successful integration. However, during its integration, it interacts exclusively with the set of systems assigned to the same target in order to exchange and update their system's tables. Accordingly, only if it is necessary to accomplish its task, the system in question may interact with the CS assigned to the same target after a successful integration.

B.5 Conclusions

The typical complex structure of SoS presents significant challenges to both systems integration and management. Consequently, advances in integration have become intensive in order to address this issue Hively and Loebl (2004), Madni and Sievers (2014).

The ability to compose a SoS out of legacy systems is a cheap and swift manner for the development. It also may have the potential to make the resulting SoS reliable, consistent, maintainable and scalable Madni and Sievers (2014). Besides, maintaining a sufficient level of interoperability of each system contributes to the endorsement of

SoS characteristics Boardman and Sauser (2006).

It is worth noting that interoperability requirements for a directed SoS are not necessarily the same as for an open SoS. Besides, CS are designed and implemented even before a need for interoperability occurs Madni and Sievers (2014), Weyns and Andersson (2013).

Obviously, interoperability offers some advantages to SoS, as endorsing scalability and flexibility in addition to the creation of new capabilities. Besides, it reduces the cost of creating new capabilities and for directed SoS and creates the illusion of an integrated system for management authorities. However, the openness of the SoS increases the technical complexity Maier (1998), Rothenberg (2008).

Conceptually, two SoS sharing the same characteristics don't necessarily adopt the same managerial and operational perspectives. Therefore, integration processes are not identical.

Another advantage of this proposition is that the adaptability of the approach pushes the capability of SoS forward to handle interdependent joint activities while conserving the viability of the performance. The proof is that CS handle the integration process by themselves. Further details are available in Ed-daoui et al. (2019b)

Appendix C

Interoperability Questionnaire

The purpose of this questionnaire is to identify the organizational, operational, technical and geographical barriers in order to be evaluated with the quantity of exchanged information. The content of the questionnaire is as follows:

Name
Activity sector
Address
Email
Phone

Q1. Annual revenue

- ☐ Less than 1 000 000 MAD
- ☐ Between 1 000 000 and 5 000 000 MAD
- ☐ More than 5 000 000

Q2. Size of the company

- ☐ Small firm: up to 50 employees
- ☐ Medium firm: 51 to 250 employees
- ☐ Large company: more than 250 employees

Q3. What are the main activities of the company?

.....

Q4. Who are the enterprise's main clients?

.....

Q5. Who are the enterprise's partners?

.....

Q6. Who are the enterprise's suppliers?

.....

Q7. Do you have partners located in ATLANTIC FREE ZONE? If yes, who are they?

.....

Q8. Do you have clients located in ATLANTIC FREE ZONE? If yes, who are they?

.....

Q9. Do you have suppliers located in ATLANTIC FREE ZONE? If yes, who are they?

.....

Evaluation of the relationship with another enterprise (client, supplier):

Name
Activity sector
Address
Email
Phone

Q10. Annual revenue

- ☐ Less than 1 000 000 MAD
- ☐ Between 1 000 000 and 5 000 000 MAD
- ☐ More than 5 000 000

Q11. Size of the company

- ☐ Small firm: up to 50 employees
- ☐ Medium firm: 51 to 250 employees
- ☐ Large company: more than 250 employees

Q12. Are authorities/responsibilities clearly defined at both sides (you and your partner)?

☐ Business

☐ Process

☐ Service

☐ Data

Q13. Does the exchange use norms/standards?

☐ Business

☐ Process

☐ Service

☐ Data

Q13. Does the exchange use norms/standards?

☐ Business

☐ Process

☐ Service

☐ Data

Q14. Are the decisions compatible between the two sides?

☐ Business

☐ Process

☐ Service

☐ Data

Q15. Are there any legislative obstacles?

☐ Business

☐ Process

☐ Service

☐ Data

Q16. Are procedures clearly defined?

☐ Business

☐ Process

☐ Service

☐ Data

Q17. Are procedures well known between the two sides?

☐ Business

☐ Process

☐ Service

☐ Data

Q18. Are the commercial approaches compatible between the two sides?

☐ Business

☐ Process

☐ Service

☐ Data

Q19. Are the enterprise's cultures compatible?

☐ Business

☐ Process

☐ Service

☐ Data

Q20. Are the methods of works compatible?

☐ Business

☐ Process

☐ Service

☐ Data

Q21. Are there geographical obstacles?

☐ Business

☐ Process

☐ Service

☐ Data

Q22. Are there any financial obstacles?

☐ Business

☐ Process

☐ Service

☐ Data

Q23. Are the IT Platform technologies compatible?

☐ Business

☐ Process

☐ Service

☐ Data

Q24. Do your company and your partner use the same protocols of exchange?

☐ Business

☐ Process

☐ Service

☐ Data

Efficiency of information exchange :

Q25. What is the total rate of exchanges with this partner during a given period (please, specify the period by day, week or month)?
.....
Q26. What is the total rate of the successful exchanges with this partner within the same period provided above?
.....
Q27. What is the rate of conforming exchanges ?
.....
Q28. What is the rate of the exploited information? .....

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