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ANALYSING ECO-SYSTEM OF '-ILITIES' FOR RESILIENCE EVALUATION IN SYSTEM OF SYSTEMS

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ABSTRACT: This paper addresses the analysis of the ecosystem of '-ilities' to formalize and evaluate the resilience in the context of the System of Systems Engineering (SoSE). It presents the very first concepts to formalize and evaluate the resilience. On the one hand, the analysis of several metrics and indicators of resilience as well as the relationship between resilience and other non-functional requirements are examined. On the other hand, the relation between other '-ilities' ecosystem and resilience are highlighted and mapped with the dynamic of the resilience allowing an accurate evaluation. A set of indicators is to be chosen to evaluate the resilience and particularly indicators that are associated with these ecosystem of '-ilities' to each zone of the resilience life-cycle. The expected benefit of such method is to allow SoS resilience characterization by analyzing the ecosystem, in order to enable its evaluation.

KEYWORDS: System of systems engineering, Resilience, Non-functional property, '-ilities' ecosystem.

1 INTRODUCTION

“A system of systems (SoS) is an integration of a finite number of constituent systems which are independent and operable, and which are networked together for a period of time to achieve a certain higher goal” (Gorod et al. 2008). According to Maier (Maier 1996), a SoS is composed of separate constituent systems and have five characteristics:

Operational Independence: If the SoS is disassembled into its component systems the component systems must be able to usefully operate independently.

Managerial Independence: The component systems are separately acquired and integrated but maintain a continuing operational existence independent of the SoS.

Evolutionary independence: SoS is not created once and for all, but evolves as constituent systems, or functions thereof, are added, removed, or modified.

Geographic distribution: The parties collaborating in a SoS are distributed over a large geographic extent.

Emergent behaviors: They are only exhibited at the SoS level and cannot be achieved by any of the constituent systems operating independently of the other constituent systems.

According to this definition, the formation of a SoS is not necessarily a permanent phenomenon, but rather a necessity for the integration and the networking in a centralized way for a specific objective. Many systems can be seen as SoS, e.g. air transport networks, Franco-German high speed train networks, smart grid system, electric power distribution networks. For instance, in a

smart grid (Figure 1), the power distribution system is independent of the provider unit system and is able to carry out its mission and it can distribute, share necessary information with other systems, as well as modify power plant in order to evolve and aggregate the desired global mission.



Figure 1: Smart grid system of systems¹

In that context, the SoS engineering (SoSE) requires having means to model, to simulate and to evaluate global behaviour of a SoS as well as a set of functional and non-functional requirements that a SoS must meet to fulfil its mission adequately. The problem addressed concerns the evaluation of non-functional requirements of SoS. It is about specifying and developing method for the evaluation of resilience, and applying this method

¹http://solutions.3m.com/wps/portal/3M/en_EU/SmartGrid/EU-Smart-Grid/

within the SoS. The proposed method aims to define mathematical model to verify if the resilience expectation is satisfied when a SoS is under design or existing. The paper is structured as follow. After this brief introduction, the problematic of this research work is pointed out. The concept of resilience is presented as well as different methods to evaluate this requirement. The next section presents the as the founding principles for the development of our approach to analyze and evaluate resilience. The final section presents the conclusion and the future perspective for this research.

2 PROBLEMATIC AND EXPECTED OUTCOMES

Among the non-functional requirements, a set is called ‘-illity’ (ISO 15288, 2011) and represents “*the desired properties of systems, such as flexibility or maintainability (usually but not always ending in ‘-ility’), that often manifest themselves after a system has been put to its initial use. These properties are not the primary functional requirements of a system’s performance, but typically concern wider system impacts with respect to time and stakeholders than are embodied in those primary functional requirements.*” (De Weck, 2012). For instance, we can mention the *flexibility, robustness, safety, interoperability* or else, *survivability*. Currently 74 to 83 ‘-ilities’ are identified in the literature. The network of ‘-ilities’ correlations schematized Figure 2 presents a set of identified ‘-ilities’ as well as their dependencies (De Weck, 2012). These dependencies show causal relationships but cannot detail the semantic nature of the link, which could include complement, substitution or other compromise between pairs of ‘-ilities’.

The proposed approach to evaluate the resilience intends to relies on the correlation network by studying and analyzing the relationships that can exists between ‘-ilities’. For instance the variation of given ‘-ilities’ that can result from the variation of another ‘-ilities’ from which it is linked. In that way, the criteria that define a given link must be defined. Thus, the here presented research work proposes to study and analyze the ‘-ilities’ ecosystem as a whole rather than to study a single ‘-ility’ in isolation and focuses on the resilience.

Resilience in the context of SoS is an important requirement because it must be mastered and maximized (Chin et al. 2013) in order to effectively cope with disruptive events and maintain acceptable levels of services and performance. It exist several definitions of resilience and usually, the resilience is defined as “*the ability of the system to resist, absorb, recover or adapt to disturbances and diminish the consequences as well as to recover quickly and effectively*” (Haimes, 2009), (Hollnagel, 2013), (Royce, 2014). Lastly, resilience is practiced in various application area *e.g.* critical infrastructure monitoring, or security (Francis & Bekera 2014), (Pflanz, 2012), (Berkeley, 2010), (Andrews, 2014).

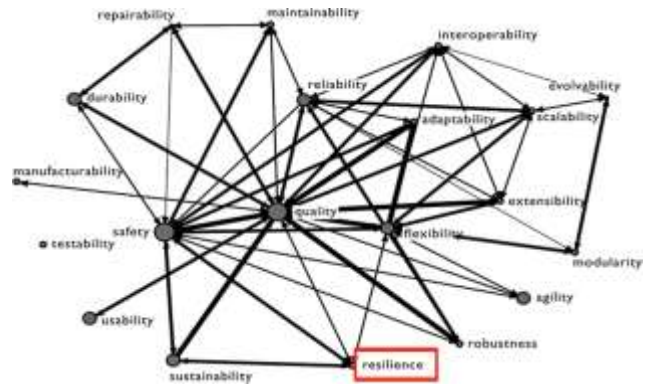


Figure 2: Correlation network of ‘-ilities’ (De Weck, 2012)

As a consequence this research work aims to define, specify and evaluate the resilience within a SoSE context. The prevention, preparation and management of negative perturbations and their effects within the framework of the security and protection of systems have become a major concern due to the increasing complexity of the SoS. The disturbance force may lead to heavy loss of performance and affect a SoS so that the measure and evaluation, of non-functional requirement such as resilience, is a part of the improvement of SoS's performance and the mitigation of negative aftermaths.

3 RESILIENCE DEFINITION AND EVALUATION: A SURVEY

3.1 Definition of resilience

Several definitions describe resilience in the literature. (Hollnagel et al. 2012) Hollnagel define the resilience as “*the ability of a system or organization to react to and recover from disturbances at an early stage with minimal effect on its dynamic stability*”. (Scott, 2010) defines resilience as a combination of avoidance, survival, and recovery and considers brittleness to be the opposite of resilient. He defines resilience as the ability of a system to absorb a disruption without loss of capability. Both suggest that resilient systems are able to manage disastrous situation due to several capacities requested throughout the classical phases of the disaster management lifecycle: **Anticipation (Preparation, Prevention)**, **Response (Absorption, Adaptation)** and **Recovery** (Figure 3).

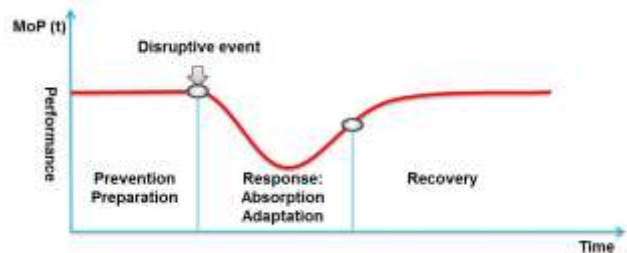


Figure 3: The classical resilience dynamic

Zone1-Anticipation (Prevention and preparedness) aims at identifying and minimizing the risks and prepara-

tion to face, its equipment and fittings, and the natural hazards of the environment (UNESCO 2017).

Zone2-Response (Absorption and Adaptation). The absorptive capability refers to an endogenous ability of a system to reduce the negative impacts caused by disruptive events and minimize consequences with less effort (Nan, 2017), (Royce, 2014). The capacity of a system to absorb negative effects can be improved during the prevention phase by increasing system's **robustness**. The adaptive capability (**adaptability**) refers to an endogenous ability of the system to adapt to disruptive events through self-organization (**flexibility, interoperability**) to minimize consequences and it can be enhanced by using emergency systems.

Zone3-Recovery is defined as a return to a qualified acceptable condition. The *restorative* capability refers to an ability of the system to rapidly be repaired (**maintainability, repairability**) and returned to an as much as possible normal and reliable functioning mode that meets the requirements for an acceptable and desirable level of quality of service and expected control (Nan, 2017). The study and synthesis of different definitions shows that authors suppose that resilience can be characterized by zone such as *Anticipation, Recovery and Response*, each ones considering more or less zone in their study (e.g. Nogal considers only the resilience as a problem of response and recovery) (Figure 4). As part of our research work to assess resilience within SoS, we consider the three areas of the dynamic of resilience, as defined by (Cox, 2011).

Anticipation	Response	Recovery	Reference
✓	✓	✓	Cox, 2011
✗	✓	✓	Nogal, 2016
✗	✓	✓	Nan, 2017
✗	✓	✓	Royce, 2014
✗	✓	✓	Garguilo, 2016
✗	✗	✓	Devanandham, 2012

Figure 4: Resilience dynamic

3.2 Evaluation of resilience

Resilience can be assessed in different ways: by measuring the performance or loss of performance of a system before and after the disruptive event, the potential loss of functionality, the loss of quality of service, the effectiveness of the security barriers, or else, the activities recovery. Whatever the way used to measure resilience, the main goal is to have information about the strengths or weaknesses of a system to prioritize actions to improve ability of resilience. Numerous works to evaluate the resilience are available in the literature e.g. (Royce, 2014) and (Zobel, 2011) each with its own points of view.

(Royce, 2014) states the measurement of resilience is a function of the 3 capacities (absorption, adaptation and recovery) as well as recovery time, through the meas-

urement of the performance and its evolution. His method is based on a resilience analysis framework and a metric for measuring resilience. His analysis framework consists of system identification, resilience objective setting, vulnerability analysis, and stakeholder engagement. (Zobel, 2010) provides a quantitative measure of resilience in the face of multiple disaster-related events. He introduces the concept of the resilience triangle, which incorporates measures of both the robustness against initial loss due to a disaster and the rapidity of the recovery process. He extends the concepts of the resilience triangle and predictive resilience in disaster by considering the trade-offs between several criteria for each event (multi events), as well as for any multi-events situation. (Chan & Fekri 2008) developed the Resiliency-Connectivity metric that measures the resilience of communication networks in the face of adversarial influences. Their measure takes into account the probability of link compromise and the probability of overall network connectivity. Their work is based on sudden disasters and the initial impact of each event as well as the recovery time of the system before the next event occurs. A mathematical model is developed for the measure of resilience. Robustness is used to increase the level of SoS resilience so that it recovers its performance and returns to an acceptable state (Figure 5), thus, the link between resilience and robustness is clearly exhibited in this measure.

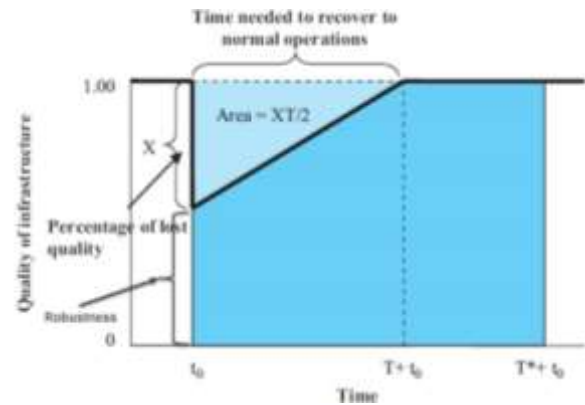


Figure 5: The predicted resilience triangle

The works presented above shows different approaches to assess resilience (Figure 6). Among these works, it is to note that Zobel highlights the link between resilience and another '-ility' (robustness in the Zone2-response and rapidity in zone3- recovery). Its measurement shows the importance of the consideration of the link between '-ilities' since the more the robustness is high, the more the resilience can be efficient in term of response. Thus, the ecosystem of '-ilities' and their relationship can be used and study to evaluate a given '-ility'.


Reference	Ecosystem of '-ilities'	Method/approach	Zone
Royce, 2014		Resilience factor	Response, Recovery
Devanandham, 2011		Potential losses	Recovery
Zobel, 2011	 (Robustness)	Loss of features	Response, Recovery

Figure 6: Synthesis of different resilience assessment methods

4 APPROACH PROPOSAL

4.1 Means of analysis of resilience and '-ilities' ecosystem

We consider the representation of the assessment of resilience by defining, analyzing and formalizing the '-ilities' ecosystem (Figure 7).

In this proposition, we focus on the analysis of the resilience and its environment and highlight the various components to evaluate the resilience. Using the ecosystem of '-ilities' in terms of evaluation and measuring the level of resilience, allows to treat resilience in a non-isolated way. The four components considered in our work are: *influence* (1), *orientation* (2), *dependence* (3) and *propagation* (4).

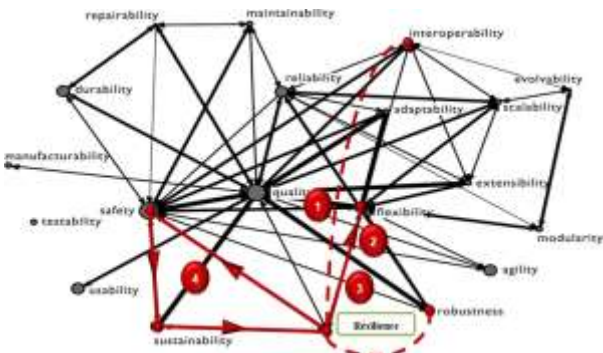


Figure 7: Correlation network of '-ilities' based on (De Weck, 2012)

4.1.1 The influence

This component aims to identify the influence between resilience and other '-ilities'. The influence is defined as *an action, exercised by one '-ility' onto another*. In other words the influence characterizes a change of a given -ility and coming from another '-ility'.

Influence is about the identification of the link between '-ilities' belonging to the network. Thus the knowledge of the influence is based on the construction of a network that consider a given '-ility' under study and links with other '-ilities' that can modify it. Some influences are identified and defined (De Weck, 2012) (Figure 7). However, as claimed (De Weck, 2012) some might exist but are not yet identified. The reason is that some '-ilities' are quite recent and other ones are not enough studied to identify possible or new links in the network. For instance, interoperability influences the resilience

but it is not highlighted in the graph. Indeed, Interoperability is *the ability of entities to communicate and interact effectively* (ISO/TC 184/SC 5 2011) so, it influences resilience since, interactions between systems to share information can support the system to adapt or mitigate to a disruptive event. In order to assess resilience based on the study resilience, it is necessary to identify all influences between resilience and other '-ilities'. The knowledge of influence will be used, further, to precise if this one is negative or positive. This aspect is important since if an influence is not identified the future defined metric and further, the evaluation will be incorrect. Currently, others influences (with resilience) than those presented in the primary graph are identified (*e.g.* interoperability, robustness). This identification relies mainly on the analysis of the literature.

4.1.2 The orientation

The orientation defines whether the influences is unidirectional (*ex.* quality *influences* resilience) or bidirectional (*ex.* quality *influences* resilience and vice versa).

Precisely, the orientation allows to know the direction of the changing, that means by which '-ilities' a given one is influenced and which ones it influences itself. This orientation must be considered "from" resilience "to" another '-ilities' as well as "from" another '-ilities' to resilience. The objective is to identify the ecosystems of '-ilities' that increase (but also decrease) the resilience of a SoS. Defining and identifying first, all the influences with resilience and their orientation, allows to get a network of '-ilities' acting as a basis to assess resilience further. Figure 8 shows the identified ecosystems of '-ilities' that influence resilience (*e.g.* interoperability, sustainability, reparability...) as well as the orientation of these influences. For instance, there is a dual direction between resilience and safety (safety ↔ resilience), meaning that by decreasing or increasing the level of safety, the resilience is impacted and vice versa.

Let's note that the two first components influence and orientation are quite generic to be applied to each '-ilities' of the graph that could be studied deeper.



Figure 8: Graph of influences and orientations for resilience assessment

4.1.3 The dependence

The dependence characterizes is the level of a studied '-ility' regarding to the level of other '-ility' by which it is influenced. The dependence expresses the operability of a given '-ility' (namely targeted -ility and noted *IOp*, for *Ilities Operability*), depending on criteria characterizing

another ‘-ility’ (namely source ‘-ility’) from which it is influenced. The operability is the ability to achieve an ‘-ility’. **Operability** is a state where an ‘-ility’ is functioning at some level (quantitative or qualitative).

The dependence relies on three aspects namely the **importance**, the **incidence** and the **state**.

The importance (noted α_s), is defined as a value that expresses the participation of the operability of the source ‘-ility’ to the operability of the target ‘-ility’. The importance scale goes from *low* to *high* and via *null*. For instance, the robustness has an importance ranked to high since the operability of the robustness influences highly the operability of the resilience.

The incidence (noted β_s) is defined as the direction of operability of the source ‘-ility’. The incidence is characterized by two directions such as *positive* and *negative*. For instance, the incidence of robustness is positive that means in the current state it is considered as good.

The state (noted γ_s) is defined as the current level of the source ‘-ility’. This level can be obtained by classical metrics or any means used usually to evaluate an ‘-ility’. For instance, the current state of robustness is high (and positive as well). In another state it could be considered as low (but always positive).

The analysis of the dependence of ecosystem of ‘-ilities’ finds its founding principles, in this work, in the methodology of the analysis of the functional dependency network (FDNA) (Paul R. Garvey & C Ariel Piento 2010). The proposed approach integrates the methodology (FDNA) on the graph of influence in order to formalize and formulate the dependence of the ‘-ilities’ network. The proposed influence graph allows a visual representation of complex dependencies between ‘-ilities’ (source, target) on the one hand and, the design of analytic formalisms that measure and trace dependencies between ‘-ilities’ on the other hand. As a consequence, we assert the ‘-ilities’ ecosystem can be represented as a directed graph whose entities are ‘-ilities’ that depict the **importance**, the **incidence** and the **state** of source – target relationships.

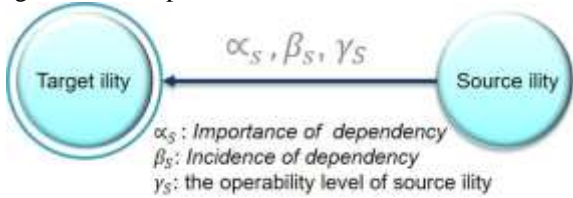


Figure 9: Graph of Dependency between a source and target ility

Thus, the evaluation of a given ility (Iop_i) is a function depending on the parameters defined above (γ_s , α_{st} and β_{st}) and can be noted:

$$Iop_T = f(\alpha_S, \beta_S, \gamma_S) \quad (1)$$

Where :

Iop_T : the operability level of target ‘-ility’

α_S : the importance of dependency

β_S : the incidence of dependency

γ_S : the operability level of source ‘-ility’

Lastly since, a target ‘-ility’ can depend on several source ‘-ility’, the operability level can be expressed by the general function such as:

$$Iop_T = f(Iop_{s1}, \dots, Iop_{sn}) \quad (2)$$

$$Iop_T = F(f(\alpha_{s1T}, \beta_{s1T}, \gamma_{s1T}) \dots f(\alpha_{snT}, \beta_{snT}, \gamma_{snT})) \quad (3)$$

Iop_T : the operability level of target ‘-ility’

α_{snT} : the importance of dependence

β_{snT} : the incidences of dependency

γ_{sn} : the incidence of operability level of sources ‘-ility’

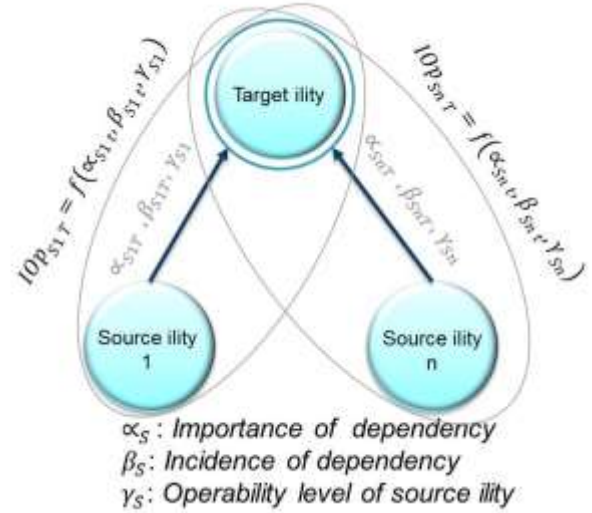


Figure 10: Model dependency relationships ‘-ilities’ ecosystem

Iop_T is obtained by, first, calculating the resulting operability of the target depending on each source Iop_{st} . Once each intermediate operability levels are obtained, they are aggregated to get the final operability level of the target Iop_T . At this stage, we focus on calculating the resulting operabilities from each ‘-ility’ source on the ‘-ility’ target and, the further step will be to define the function allowing to aggregate each operability to get the final operability of the target.

4.1.4 The propagation

The propagation represents a relation “starting from” an ‘-ility’ and returning to this ‘-ility’ *via* another ‘-ilities’ (e.g. resilience → safety → sustainability → resilience). At this stage, we consider and limit the propagation study to a chain of 3 ‘-ilities’. In this section, we present the ‘-ilities’ that have links with the resilience and thus we analyze their relations by practicing the components defined above (influence, orientation, dependence). For instance, figure 11 show the *sustainability* influences the *resilience*, the *resilience* influences the *safety* and finally, the *safety* influences the *sustainability*. That means that a variation in sustainability leads and propagates to a variation in resilience and a variation in resilience leads to a variation in safety and finally leads to variation in sustainability.

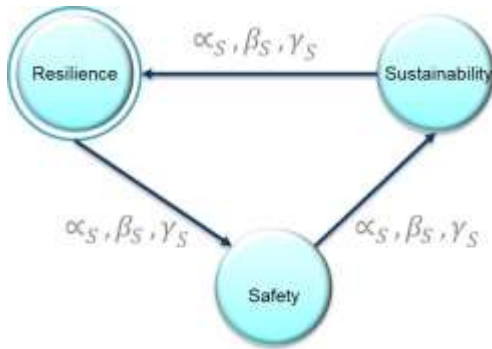


Figure 11: ‘-ilities’ ecosystem Graph Models Dependence Relationships

The problematic inherent to this chain (and more widely to the propagation) is to find and start from an initial -ility that allows to analyse the chain. Then the analysis can start relying on the principles of dependence as defined previously. From this stage, the modifications are propagated through the chain until to back on the initial ility. In that case, the obtained results for each -ility belonging to the chain must be analyzed. In this current state, our research attempts to develop mechanisms to analyse the chain of -ility.

Figure 12 summarizes the relation between resilience and sustainability in agreements with the four components for the relation analysis and evaluation. In this end, each relationship between resilience and other ‘-ilities’ (which impact resilience) have to be identified and formalized. In the same way the components such as dependence and propagation must formally established in order to allow the evaluation of the resilience (e.g. quantification or qualification of “high increase” or else definition of effect in the propagation chain).

Influence	Orientation	Dependance	Propagation
Resilience-Sustainability	S → R	Strength Criticality (α, β, γ)	

Figure 12: Characterization of the relation between resilience and sustainability

4.2 Resilience evaluation according to its dynamic

The resilience life-cycle (Figure 3) (*anticipation, response and recovery*) must be considered. Indeed, the aim is to know the level of resilience for each considered zone in order to implement adapted solution to improve resilience if a specific zone is failing. To this purpose, ‘-ilities’ ecosystem and their influences are mapped in each zone of the dynamic of resilience (e.g. flexibility can be expected during the prevention, Figure 13). This positioning is relative to the analysis of resilience and ‘-ilities’ ecosystem that have an identified links in each area. The objective is to get a resilience indicator for each zone in order to identify precisely a problem of resilience. In the end, the aggregation of each indicator will provide an evaluation of the resilience of the SoS.

Figure 13 shows the mapping of all the ‘-ilities’ that is identified and positioned in different phases of resilience life-cycle, sometimes in various phases (e.g. flexibility is positioned in zone 2, zone 3 and robustness in zone 1, zone 2, zone 3). Mapping makes it possible to establish the resilience indicators associated with these ‘-ilities’ and for each zone of belonging. These indicators ultimately enable the level of resilience to be accurately identified and assessed, so aggregation of all these indicators will provide an assessment of the overall resilience of the SoS. The novelty of this method is the analysis of resilience in the network of ‘-ilities’, so as to analyse globally the ‘-ilities’ that influence resilience without having to study them in isolation. All ‘-ilities’ that influence resilience have been identified. In order to assess resilience in the ‘-ilities’ ecosystem without having to consider all the ‘-ilities’ (it may not be all relevant depending on the system), the user will choose the ‘-ilities’ that have the most impact and important on the system. The choice of ‘-ilities’ to consider as a priority must be based on the life cycle of ‘-ility’.

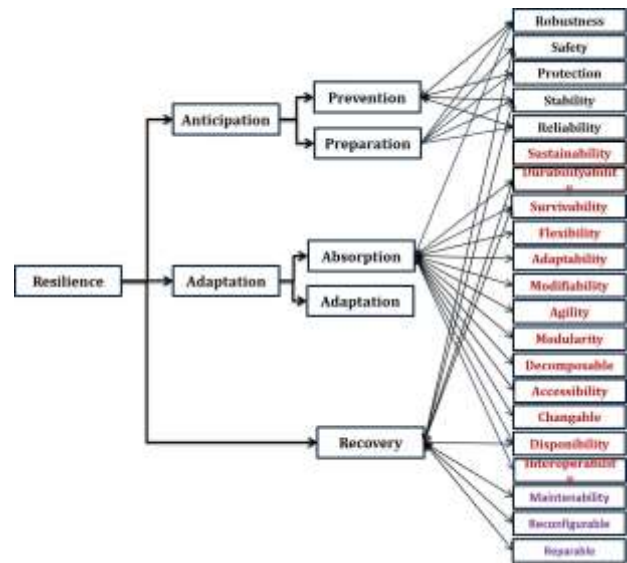


Figure 13: Resilience dynamic and ‘-Iilities’ Mapping

5 CONCLUSION

The very first development of the here presented work aims, in the end, to evaluate the resilience in the context of SoSE relying on the dynamic of the resilience and on the study of the resilience as an ‘-ilities’ belonging to a wider set of ‘-ilities’. On the one hand, several resilience metrics are studied and analyzed as well as the relationship between resilience and the other ‘-ilities’ ecosystem. On the other hand the ‘-ilities’ ecosystem and their dependencies (influences) are mapped by positioning them according to the dynamic of resilience. In order to assess resilience, we will assign an indicator associated to each zone of resilience. We presented a graph model of ‘-ilities’ ecosystem that influence resilience and the main components are identified and highlighted and will be developed in the next steps in order to evaluate resilience. Future work is related to the formalization and

development of indicators to evaluate resilience as well as mechanisms to study the propagation in the network.

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