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► To cite this version:

Weppe Alexandre, Nicolas Daclin, Tixier Jérôme, Aurélia Bony-Dandrieux. Building of a new framework for resilience assessment based on an ecosystem of ” -ilities”. Congrès Lambda Mu 23 “ Innovations et maîtrise des risques pour un avenir durable ” - 23e Congrès de Maîtrise des Risques et de Sûreté de Fonctionnement, Institut pour la Maîtrise des Risques, Oct 2022, Paris Saclay, France. hal-03966591

HAL Id: hal-03966591

<https://hal.science/hal-03966591>

Submitted on 31 Jan 2023

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Building of a new framework for resilience assessment based on an ecosystem of " -ilities"

Construction d'un nouveau cadre d'évaluation de la résilience basé sur un écosystème d'" -ilities"

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Résumé — Le contexte géopolitique et le changement climatique ont entraîné un nombre croissant d'accidents et de catastrophes au cours des vingt dernières années. En particulier, les Infrastructures Critiques (IC, ex : système de distribution d'eau, système de santé, etc...) essentielles aux sociétés, subissent de plus en plus les conséquences de ces catastrophes. Ces IC, de plus en plus complexes, doivent faire face à ces catastrophes afin de maintenir un service acceptable pour la société et d'éviter la propagation de la catastrophe sur d'autres systèmes et IC. Afin de gérer ce type de problème, le concept de résilience est le meilleur candidat. L'objectif de cette recherche est de pouvoir évaluer la résilience afin d'améliorer la gestion d'un CI en cas de désastre. Ce travail fait partie d'un projet de recherche ANR (Résilience des infrastructures et des systèmes interconnectés, 18-CE39-0018-05).

Mots-clefs — *résilience, évaluation, « -ilities », méthode, cadre d'évaluation*

Abstract — The geopolitical context and climate change have led to an increasing number of accidents and disasters over the last twenty years. In particular, Critical Infrastructures (CI, e.g.: water distribution system, health system, etc...) essential to societies, are increasingly suffering the consequences of these disasters. These CIs, more and more complex, have to face these disasters in order to maintain an acceptable service to the society and to avoid the propagation of the disaster on other systems and CIs. In order to manage this type of problem, the concept of resilience is the best candidate. The goal of this research is to be able to evaluate resilience in order to improve the management of a CI in case of disaster. This work is part of an ANR research project (Resilience of infrastructures and interconnected systems, 18-CE39-0018-05).

Keywords — *resilience, assessment, “-ilities”, framework, method*

I. INTRODUCTION

Increasingly, our societies rely on systems considered as vital and known as critical infrastructures (CI). These CI are characterized by two aspects, (1) their essential character for our societies, and (2) their (inter)dependence with other critical systems.

A CI is defined as "a system or part of it [...], which is essential to the maintenance of vital functions of society, public health, safety and economic or social well-being of citizens. Its failure, incapacity or destruction will have a debilitating impact on the country". [14]

Thus, an event that disrupts the functioning of a CI can have major consequences on its own activity but also on the systems with which it is connected. In order to help the CI to manage this type of situation, the use of the concept of resilience is an excellent opportunity. The objective of this research is to propose a new approach to evaluate resilience, in order to help the infrastructure manager to face situations characterized by a dreaded event. For the last ten years, resilience has been a key concept in research. Originally, almost exclusively characterized by the performance of the system, recent works show that resilience can also be characterized via other concepts or properties such as safety, security, reliability or robustness for example.

This paper presents the first version of a framework for resilience assessment through a new vision based on (1) an ecosystem of "-ilities", (2) the phases of resilience and the system's points of view and (3) specific assessment operators.

Resilience is seen as an “-ility” [43], [33]. The specificity of the method is to assess resilience through the analysis of an ecosystem connecting different “-ilities”.

The assessment method is applied in several steps:

1. Building a list of “-ilities” and formalizing the relationships between them,
2. Creating an ecosystem of “-ilities”, centered on the assessed “-ility”,
3. Resilience assessment framework: layers and sub-systems,
4. Construction of evaluation operators,
5. Evaluation.

This work is part of an ANR research project (Resilience of infrastructures and interconnected systems, 18-CE39-0018-05), which furnish us data and an application case: a higher education institution.

II. LITERATURE REVIEW

A. Resilience

Originally, resilience was defined for specific fields such as strength of materials and psychology:

- Firstly, in the technical field, resilience is defined as "a quantity which corresponds to the energy required per unit area to cause the breakage of a sample of a given shape and size" [16].

- In the field of psychology, resilience is "the ability to cope with hardship, to find internal resources and external support, to implement psychological mechanisms to overcome trauma" (definition from the French dictionary).

The literature offers many definitions of resilience. At least 70 definitions can be found, without claiming to be exhaustive. These definitions are adapted by the authors to the fields of application in which resilience will be implemented (physics [16], ecology [18], [19], [24], [47], social systems [2], [1], [37], [38], sociology of the individual [31], [5], economic systems [42], [27], transport systems [35], systems engineering [22], [6], [25], etc.) on the one hand, and in relation to the disruptive events likely to occur on the other.

Although the above definitions apply to different domains, they all have common characteristics (absorption, recovery, adaptation, intensity reduction, learning, self-organization). Cutter's very generic definition captures all of these characteristics by defining resilience as "the ability to anticipate, prepare for, respond to, adapt to and mitigate the consequences of disturbances, and to recover quickly and effectively, including through restoration, preservation of services" [10].

Furthermore, according to [9], the resilience of a critical infrastructure depends on its capabilities related to four dimensions:

- **Technical** - ability to perform the function, at a required level, during and after an adverse event;
- **Organizational** - the ability of organizations to manage facilities, maintain key functions and make

decisions to maintain/improve the situation during the event;

- **Human** - measures specifically designed to reduce the level at which communities and government jurisdictions may suffer consequences due to the loss of critical services as a result of an event; Human behavior during catastrophic events;
- **Economic** - ability to reduce direct and indirect economic losses, allocation of resources, business continuity.

Furthermore, according to [22], resilience should be integrated into the thinking process as early as possible, especially when a new product/system is to be designed, which [40] expresses as: "resilience, should be identified upstream, i.e., at the design stage rather than taking additional factors into account later". Finally, according to [12], resilience is a fully identified non-functional requirement which "is desired and often occurs after operational readiness".

However, these definitions still retain the original essence of resilience, i.e., the ability to cope, to bounce back, and specify it with different characteristics such as preparedness, prevention, absorption, adaptation or recovery. It is therefore these characteristics that a system will seek to develop as a priority to improve its resilience capacity.

Lastly, resilience is characterized temporally by a three-phase dynamic which can impact the performance of a system. Although this dynamic is clearly identified, not all authors consider resilience these three phases. In this sense, some may consider that resilience is only a matter of anticipation or response and recovery.

TABLE I. DEFINITION OF RESILIENCE ACCORDING TO ITS DYNAMICS AND DIFFERENT VISIONS

| References | Anticipation | | Response | | Recovery |
|---|--------------|-------------|------------|------------|----------|
| | Prevention | Preparation | Absorption | Adaptation | |
| • Madni et al. 2009 | √ | √ | | √ | √ |
| • Westrum 2006 | √ | √ | | | √ |
| • Vogus et al. 2007 • Mileti 1999 • Longstaff 205 • Kahan et al. 2009 | | | √ | | √ |
| • Seville et al. 2008 | | | √ | √ | |
| • Bruneau et al. 2003 • Nan et al. 2017 • Royce et al. 2014 • Gargiulo et al. 2016 | | | √ | √ | √ |
| • Henry et al. 2012 | | | | | √ |
| • Brunsdon et al. 2005 | √ | √ | √ | √ | |
| • Hollnagel 2011 • Cox et al. 2011 • Cutter et al. 2013b | √ | √ | √ | √ | √ |

This does not call into question the definitions of resilience discussed above, but in analyzing resilience, it is important to consider different perspectives and aggregate them into a comprehensive view. Indeed, each phase have a set of characteristics and capabilities that need to be controlled Furthermore, a capability developed for one phase may impact other phases. For example, the capacity developed to anticipate the event can be deployed to respond to the event and limit its consequences.

B. Resilience assessment

For [34], "resilience analysis has become a proactive approach to improving the ability of infrastructure to prevent damage before events, mitigate losses during events and improve recovery after events".

Similarly, for [17], resilience measurement can be used for the development of resilient systems and effective resilience strategies, and for [19], it allows to:

- Anticipate and absorb failures;
- Develop ways for the system to adapt to change and respond to the event;
- Recover to return to an acceptable mode of operation as quickly as possible.

Thus, measuring resilience is essential to develop resilient systems or improving resilience. However, the development of a sufficiently generic assessment method that considers all aspects of resilience remains difficult due to its complexity. Several methods exist for resilience assessment. Moreover, they focus on the different phases of resilience dynamics (and not all). These methods focus on:

- The performance or loss of performance of a system before and after the disruptive event [44], [36], [39], [26];
- The measurement of potential losses of system functionality [17], [50];
- Loss of quality of service before and after the disruptive event [3], [7];
- Measuring the effectiveness of safety barriers [13];
- Measurement of recovery activities [41], [8].

In addition, each assessment method focuses on only one aspect of the system (safety, quality of service, performance, etc.). To try to cover all the aspects above-mentioned and the idea is to place resilience in an ecosystem of system properties to account for all the characteristics of resilience. In systems engineering discipline, these properties are known as the "-ilities".

The aims of this research are to develop a generic resilience assessment method for critical infrastructure. By being generic, the assessment model has to cover all phases of the life cycle (Anticipation, Preparedness, Prevention, Response, Absorption, Adaptation and Recovery), the resilience perspectives (technical, organizational, social and economic).

III. ECOSYSTEM OF "-ILITIES"

An ecosystem of "-ilities" is defined as a **list of "-ilities"**, where there are **relations** connecting each "-ility". These relations represent the impact of "-ilities between each other. For example [12] show one of the first ecosystem of "-ilities".

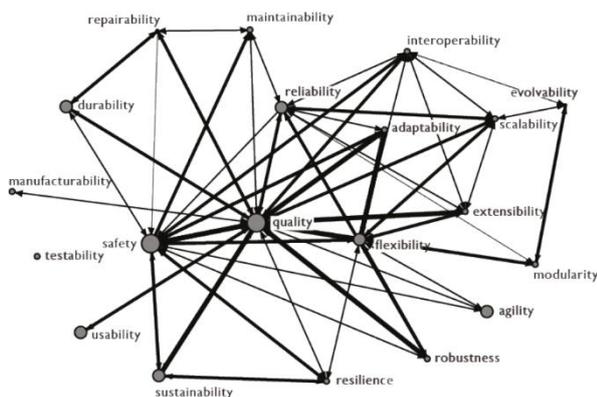


Figure 1 Eco-system of "-ilities" proposed by DeWeck 2012

A. Work list of "-ilities"

The proposed assessment method is based on an ecosystem of "-ilities". In order to construct this ecosystem, a coherent list of "-ilities" is needed. In addition, we need to identify and formalize the relationships between these "-ilities" to build a complete ecosystem. The literature review allows us to identify 3 mains contributions:

- Ross et al., (2011) [43] with 80 "-ilities".
- Willis et al., (2011) [49] with 56 "-ilities".
- Moradi, (2019) [33] with 22 "-ilities".

We then concatenated these three lists to obtain a working list of 97 "-ilities" which have each a specific definition. In these papers, there are not the definitions of the "-ilities". So, we define these ones with other articles from the literature. According to the difficulty in working with so many objects, this list must be reduced. In this aim, 3 reduction rules were defined:

Rule 1: In case of overlapping definitions between two (or more) "-ilities", only the best known and most studied "-ility" is kept.

In the first list of "-ilities" (97), the identified "-ilities" are not all formalized or defined by consensus. Some "-ilities" have very similar definitions or have not even been studied by the scientific community. For example, "securability" proposed by Ross et al. [43] is not precisely defined in the literature (with a sufficient level of precision for our evaluation purposes). But "security", proposed by Moradi 2019 [33], is widely studied, defined and formalized. We therefore choose to retain only the "security".

Rule 2: If an "-ility" is not applicable to our case study, it is removed from the list,

Some "-ilities" do not make sense for certain systems, i.e., they have been created and defined for use in one specific domain and do not necessarily have applicability in another. For example, the "installability" proposed by Ross et al. 2011 [43] does not make sense for a higher education institution (our case study). In this case, it is removed from the working list.

Rule 3: If an "-ility" is not related, with their respective definitions, to resilience in the first or second degree, it is removed from the list [33],

The application of these three rules leads to a reduction of the initial list to 24 "-ilities" in addition to resilience.

B. Relations between "-ilities"

Relationships indicate a link between one or more source "-ilities" on a target "-ility". Three parameters are used to characterize relationships as shown here:

- Orientation: A relationship is oriented from a source(s) to a target,
- Impact: A relationship characterizes an impact from the source(s) to the target,
- Uniqueness: The target is unique; a relation cannot point to several "-ilities".

So far, five types of relationships are identified and classified into two categories: influence and cooperation. The number of relationship types can evolve if other relationships are highlighted in the future.

1) The influence relationships

Two types of influence relationships between "-ilities" are defined: positive influence (denoted as "+") and negative influence (denoted as "-").

An influence accounts for a variation in a target "-ility" as a function of the variation in a source "-ility". More formally, this is expressed as

Target "-ility" value = f (source "-ility" value), where f is the function of the influence relationship.

Five relationships have been identified so far. However, the generality of the method allows for more to be added if the end user of the method thinks it necessary.

This step consists in building an ecosystem thanks to the work done in the previous step. This ecosystem is special because it focuses on the “-ility” to be assessed, i.e., resilience.

This construction of the global ecosystem is done via:

1. The definitions of the “-ilities”. The definitions of the “-ilities” show a possible links between them.
2. Expert opinions. If experts do not consider the ecosystem detailed in point 1 as relevant, they can add or remove relationships. In practice, the experts are experts of the system, for example, managers, stakeholders, etc.

In this step, the existence of the relationship between the “-ilities” and the orientation of the relationship is identified. In our case, we need to identify influences and cooperation, through the two points above mentioned.

Below is an example of an ecosystem focused on resilience.

The example in Figure 2, only represents the existence of relationships not their nature (e.g., influences, compensations...). Finally, the ecosystem will also represent the nature of the relationships (influence positive or negative, compensation, etc.) highlighted in the figure, below. A priori, the relationships of the ecosystem will always be the same whatever the context. That is, a relationship between a “-ility” A and a “-ility” B will always be the same, whatever the system under study. For example, the relationship between resilience and robustness will always be a positive influence. Similarly, the relationship between robustness and flexibility will always be a negative influence.

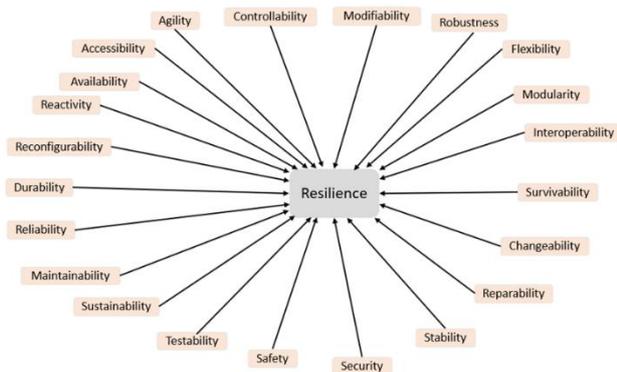


Figure 2 Conceptual diagram of an overall “-ility” ecosystem focused on resilience

The example in Figure 2 is not complete. Indeed, only the relationships between a source “-ility” and the target resilience are represented. It is necessary to finish the construction of the global ecosystem by:

- Identifying other relationships such as cooperation,
- Identifying relationships between peripheral “-ilities” (“-ilities” other than resilience, such as a relationship between robustness and flexibility for example). This identification will allow to have a

more robust ecosystem, a priori, for a better evaluation of resilience in the future.

The representation of the all relations will be a matrix to see all these without a too much charged graph.

TABLE IV. MATRIX OF RELATIONS BETWEEN “-ILITIES”

| | Accessibility | Agility | Changeability | Controlability | Availability | Durability | Interoperability | Reliability | Flexibility | Maintainability | Modifiability | Modularity | Reconfigurability | Reactivity | Reparability | Robustness | Safety | Security | Stability | Survivability | Sustainability | Testability |
|-------------------|---------------|---------|---------------|----------------|--------------|------------|------------------|-------------|-------------|-----------------|---------------|------------|-------------------|------------|--------------|------------|--------|----------|-----------|---------------|----------------|-------------|
| Accessibility | X | | | X | | | | | | X | X | | X | X | X | | X | X | | | | X |
| Agility | | X | X | | | X | X | | | | X | | X | X | | X | | | X | | X | |
| Changeability | | X | X | | | X | X | X | X | | X | X | X | | X | | | | | | X | |
| Controlability | | X | | X | | X | | X | | X | | | | | | | X | X | X | | | |
| Availability | | | | | X | | | | | | | | | | | | | | | | | |
| Durability | | | | | X | X | | X | | | | | | | | | | | | | X | |
| Interoperability | X | X | X | X | | | X | | | | | | X | X | | | X | X | X | X | | X |
| Reliability | | | | | X | X | X | X | | | | | | | | X | X | X | | X | | |
| Flexibility | | X | X | | X | | X | | X | | X | X | X | X | | X | X | X | X | X | | |
| Maintainability | | | | | X | X | | X | | X | | | | | X | X | X | X | | X | X | |
| Modifiability | | X | X | X | | X | | X | X | X | X | | | X | | X | X | X | X | X | X | |
| Modularity | | X | X | | | X | X | | X | X | X | X | | | X | | | | | X | X | |
| Reconfigurability | | X | X | X | | X | X | | X | | X | | X | | | X | | | X | X | X | |
| Reactivity | | X | | X | | | | X | | | | | | X | | | X | X | X | X | X | |
| Reparability | | | | | X | X | | X | | X | | | | X | | X | X | X | X | X | X | |
| Robustness | | X | X | | X | X | | X | X | | | | | | | X | X | X | X | X | | |
| Safety | | | | | X | X | | | | | | | | | | X | X | X | X | X | | |
| Security | X | | | | X | X | | | | | | | | | | X | X | X | X | X | | |
| Stability | | X | X | | | X | | | | | | | | | | X | X | X | X | X | | |
| Survivability | | | | | X | X | | | | | | | | | | X | X | | | X | X | |
| Sustainability | | | | | | X | | | X | | | | | | | | | | | X | X | |
| Testability | | | | X | | X | | X | | X | | | | | X | X | X | X | X | X | X | X |

This matrix permit to well represent each relation between each "-ility".

IV. EVALUATION FRAMEWORK

The global ecosystem that has been constructed is currently unusable. Indeed, it does not reflect the reality of the resilience. In particular, it does not reflect the dynamics (the life cycle) of resilience, nor the plurality of points of view (POV) of our system model, which is necessary for resilience assessment.

It is therefore necessary to provide an **assessment framework** which is the intersection of a life-cycle phase dimension of resilience and a POV dimension of the system model.

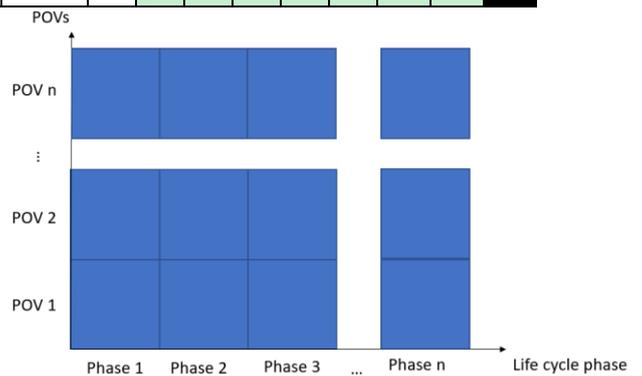


Figure 3 Conceptual diagram of the evaluation framework: the evaluation rectangle

Within each intersection of the assessment rectangle is a Layer which allows the overall ecosystem to be filtered into sub-ecosystems in order to have a better resilience assessment. To get the best resilience evaluation, we have to evaluate resilience in each sub-ecosystem.

We define a Layer as the intersection between a POV of the system model and a phase of the life cycle of the "-ility" being assessed and providing a reduced ecosystem (from the initial

global ecosystem) at the POV and phase under consideration. The layer, applied to the global ecosystem (Fig. 2), permit us to develop the sub-ecosystems (Fig. 4 and 5).

As a reminder, the life cycle of resilience is:

- Anticipation:
 - Preparation,
 - Prevention,
- Response,
 - Absorption,
 - Adaptation,
- Recovery.

In each of the phases or sub-phases of the resilience life cycle, the "-ilities" related to resilience may vary. For example, robustness is related to resilience in the preparedness phase, but not in the recovery phase.

The decomposition into POVs, on the other hand, allows a filtering of the overall ecosystem, in the same way as the phases of the life cycle, allows a more specific framework to be given to the "-ilities" of the ecosystem. Indeed, even if each "-ility" has a generic definition, it can be specified according to the domain, the business, etc. This specificity will be translated by the POVs. For example, robustness is defined as "the ability to protect and prepare a system against

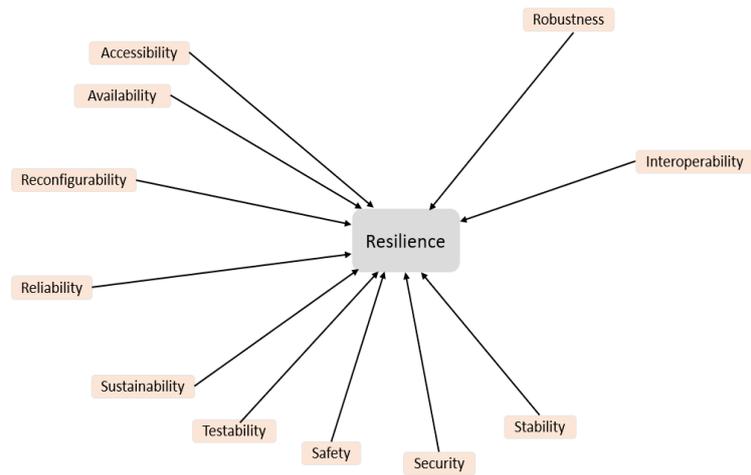


Figure 4 Sub-ecosystem of the layer (prevention, organizational)

Figure 4 represents the sub-ecosystem of the layer (prevention, organizational). It is built on crossing the filter prevention and the filter organizational. A filter has two types, a life cycle type and a POV type. A life cycle filter removes all the "-ilities" which are not applicable in the given life cycle phase. A POV filter removes all the "-ilities" which are not applicable in the given POV. These sub-ecosystems (Fig. 4) are represented in Figure 5 for all the layers.

The intersection of these two filters (life cycle phase, POV) gives a layer giving a resilience assessment rectangle.

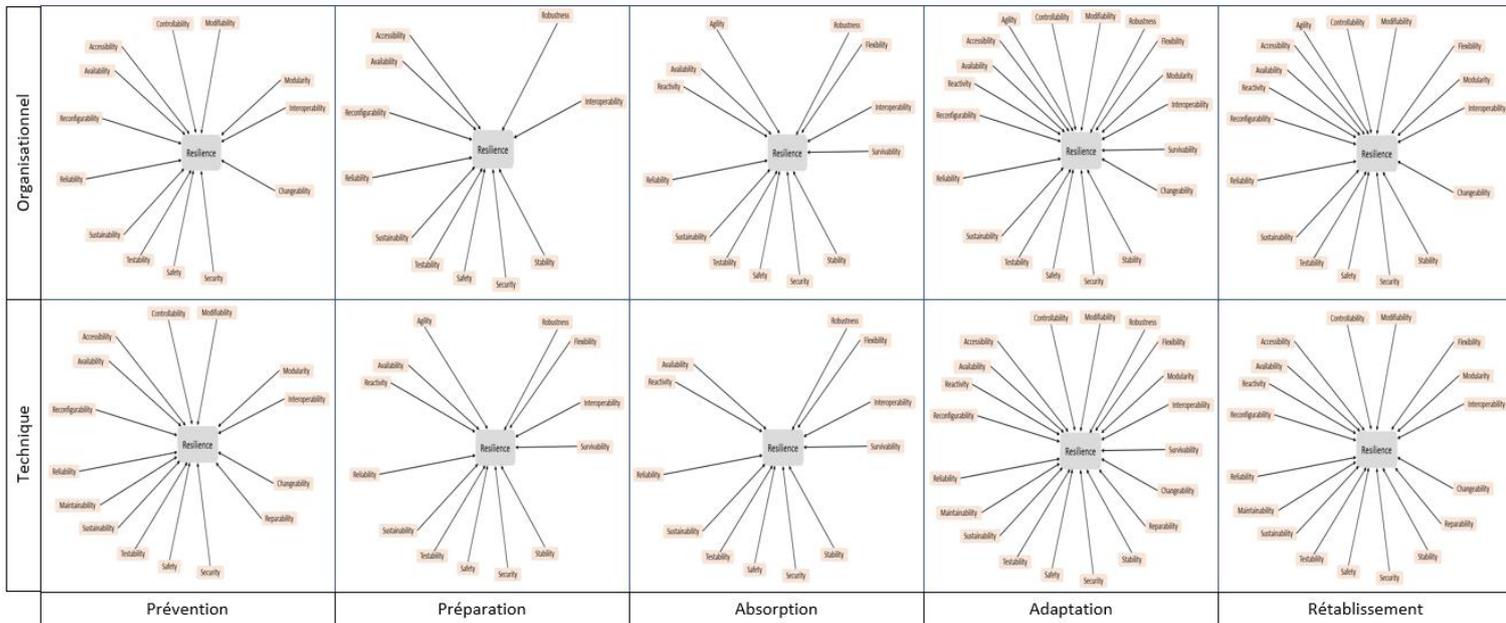


Figure 5 Resilience assessment rectangle for organizational and technical POVs

external and internal hazards. The ability of the system to withstand a predictable set of disturbances of a priori modest magnitude [29]. Nevertheless, the robustness of a wall and the robustness of a process are two concepts that make sense, but the attributes behind each are different.

With this approach, the manager can assess the resilience of his infrastructure in a global way, i.e., for the whole of the life cycle and the viewpoints. He can also focus his attention on one of the phases of the life cycle of his infrastructure to help him improve the resilience of his infrastructure. Each sub-ecosystem (Fig. 5) permit to evaluate a part of resilience. Each of these evaluations, called an outcome, permit the manager to target his intervention to upgrade resilience in his

system.

The sub-ecosystems are being developed.

Furthermore, the POVs presented above are only examples of a test case. It is quite possible to generalize this method to other POVs that might be of interest to an end-user, such as an economic POV or a social POV as presented by [9].

V. FUTUR WORKS: EVALUATION OPERATORS AND AGGREGATION

A. Evaluation operators

This step focuses on the construction of evaluation operators. An evaluation operator formally characterizes a relationship. We will therefore have a positive influence operator, a negative influence operator, a compensation operator, etc.

In a first step, we characterize the relationships through criteria. These criteria are conceptualized to move, at the next step, towards the formalization of the evaluation operators.

At this stage, there two criteria are considered: temporal and value.

The temporal criterion characterizes the temporality of the relationship, i.e., whether the relationship is limited or unlimited in time.

The value criterion characterizes the values of the source “-ility” and the target “-ility”. The values of the “-ilities” will be obtained via calculation operators or by expert opinion.

This stage is in its very early development.

The concept of criteria will enable to better characterize the relationships and, at the end, to construct the evaluation operators, which are essential to the evaluation of resilience.

Concretely, an evaluation operator is a mathematical formula which the parameters are the criterions of the relation. For example, if the evaluation operator of the “influence +” is a linear function, we have to determine the criterions of the evaluation operators.

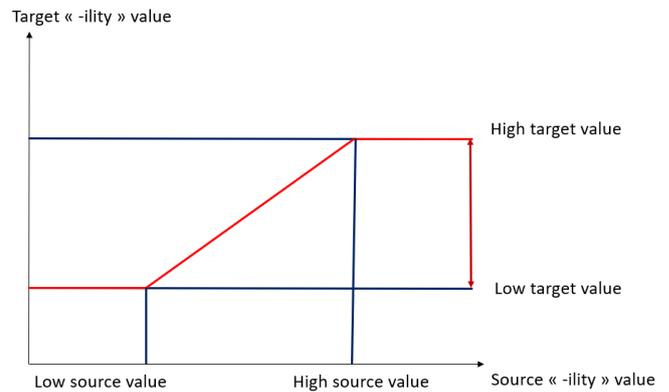


Figure 5 Example of an evaluation operator of the “influence +”

Here the temporal criterion is “illimited”. It means the relation “influence +” is always applied between the two “-ilities”. The value criterion is (low source value, high source value, low target value, high target value). These two criterions permit to determine the evaluation operator which the graphical representation is on Figure 5.

Moreover, an operator is a priori unique with respect to the relationship it formalizes. Nevertheless, from one system to another, the relationship identified between an “-ility” A and an “-ility” B may be more important than another between a “-ility” C and a “-ility” D. For example, one could imagine that the relationship (robustness, resilience) is more important than the relationship (flexibility, resilience) for a given system. A weighting of each relationship identified in our global ecosystem, and a fortiori in the sub-ecosystems, will allow to represent this specificity of the system studied.

In our example, the relationship (robustness, resilience) will have a heavier weight than the relationship (flexibility, resilience).

B. Aggregation of the results

This fifth and final step describes the linking of all the results stemming from the previous steps. That is, obtaining resilience assessment results from the sub-ecosystems and the assessment operators.

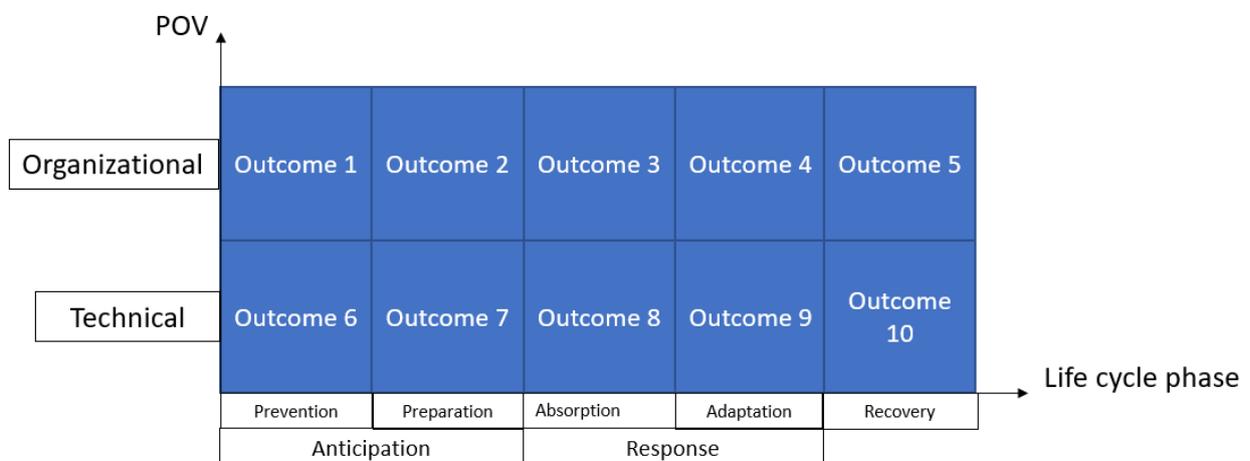


Figure 6 Resilience assessment rectangle with outcomes

As explained, if we couple the sub-ecosystems with the

assessment operators, we can have a result for each sub-ecosystem.

Here, the results, from 1 to 10, are the results of a sub-ecosystem (POV, life cycle) coupled to the evaluation operators. The operators are weighted according to the system studied.

Each of the outcomes represents a partial result. Outcome 1 is the organizational resilience for the prevention phase. Outcome 9 is the technical resilience of the adaptation phase. Depending on the choice of end-user, more generic resilience outcomes could be imagined, such as overall system resilience, system resilience in the absorption or response phase, or even viewpoint resilience such as overall technical resilience.

To have this type of assessment, we could aggregate some of the results of the assessment rectangle.

For example, in the rectangle shown in Figure 6, to have an assessment of resilience during the preparedness phase, we could aggregate Outcome 2 and Outcome 7.

Then, to obtain an assessment of the technical resilience of the system, the results should be aggregated from 6 to 10.

And finally, to obtain the overall resilience of the system, we would have to aggregate all the results from the rectangle.

We will have to determine one or more aggregation operators to perform the kind of operation presented above.

Moreover, the different results do not necessarily have the same preponderance. An end-user may consider one result of the evaluation rectangle more important than another. A weighting of these results will probably be necessary to aggregate the different evaluation results.

Secondly, an aggregation operation is likely to involve offsetting the results. That is, in the example, a good value for outcome 1 may compensate for a bad value for outcome 2. This type of compensation may lead to an evaluation bias that will have to be reported, or even measured, for the end-user.

VI. CONCLUSION

This paper covers the different steps to be implemented to create the resilience assessment model:

- Construction of a list of “-ilities” and formalization of relationships between “-ilities”,
- Creation of an ecosystem of “-ilities”,
- Resilience assessment framework: layers and sub-ecosystems,
- Construction of evaluation operators,
- Aggregation and evaluation.

These different steps provide a tooling, a framework and a decomposition of the resilience assessment, in order to operationalize it as well as possible. This decomposition is in two dimensions. First, a decomposition about the life cycle of

the resilience. Second, a decomposition about the point of view of the resilience. These decompositions, about life cycle and POV, permit to create sub-ecosystems (Figure 4 and 5) of the general ecosystem (Figure 2). These sub-ecosystems, coupled with the evaluation operators, report a realistic evaluation of the resilience, for a better management of the CI.

The three first steps of the method are quite well advanced. The two last are already in progress but only few ideas have been proposed as presented in this paper.

To finalize, this method will be equipped to models of the CI. These models will permit simulations of different scenarios, which simulate behaviors of the system. And these simulations will permit to test our method, and, finally, to help managers to manage their CI.

This work is done in the frame of the project RESIIST supported by the French research agency ANR (Résilience des infrastructures et systèmes interconnectés, 18-CE39-0018-05).

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