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An innovative approach for ongoing assessment of critical infrastructures' resilience based on a non-functional requirement ecosystem

WEPPE Alexandre

Laboratoire des Sciences des Risques (LSR), IMT Mines Ales, Ales, France. E-mail: alexandre.weppe@mines-ales.fr

BONY-DANDRIEUX Aurélia

Laboratoire des Sciences des Risques (LSR), IMT Mines Ales, Ales, France. E-mail: aurelia.bony-dandrieux@mines-ales.fr

TIXIER Jérôme

Laboratoire des Sciences des Risques (LSR), IMT Mines Ales, Ales, France. E-mail : jerome.tixier@mines-ales.fr

CHAPURLAT Vincent

Laboratoire des Sciences des Risques (LSR), IMT Mines Ales, Ales, France. E-mail: vincent.chapurlat@mines-ales.fr

KAMISSOKO Daouda

Centre Génie Industriel, IMT Mines Albi, Albi, France. E-mail: daouda.kamissoko@mines-albi.fr

DACLIN Nicolas

Laboratoire des Sciences des Risques (LSR), IMT Mines Ales, Ales, France. E-mail: nicolas.daclin@mines-ales.fr

Geopolitical context or climate change induced more and more disasters in the two last decades. Particularly, Critical Infrastructures (CI - e.g., water distribution, health care) that support the daily life of societies are impacted by these disasters. These CI are indeed essential. By their various interactions and links, they become more fragile when facing complex situations. For instance, a local event, occurring in a CI (e.g., an accident), can propagate throughout these interactions, impacting other CI, leading to a higher intensity and to a global impact. Classical risks analysis is limited in terms of global and dynamic vision of these CI, to manage these events efficiently and to recover to an acceptable functioning state for the end users. To this purpose, resilience is a useful concept, highlighted by numerous research works and organizations to characterize the best way a CI has to react to an undesirable event and avoid, if possible, its propagation. The purpose of this paper is to present the main principles of a methodology to assess and analyze resilience of a CI based on a multi views and systemic model formalized as a digital twin. 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) to provide scenarios to test and evaluate the proposed methodology.

Keywords: Resilience, non-functional requirement, -ility, digital twin, modeling, simulation

1. Introduction

In a context of geopolitical tension (e.g., a terrorist attack [1] or a pandemic situation [2]) and climate change with its extreme weather events, it appears necessary to change the management of Critical Infrastructures (CI) to manage and minimize impact of such events on the level of Quality of Service (QoS) for the people.

A CI is defined as “*a system or part of it [...], which is essential to the upkeep of the vital functions of the society, public health, safety, security and the economic or social well-being of the citizens. Its failure, its incapacity or its destruction will have a debilitating impact on the country*” [15]. It is often composed of an assembly components and sub-systems more or less themselves complex, from various and heterogeneous origins i.e., human (operators, customers, or managers...), organizations, buildings and technical means. These components interact together and

with other components form other CI. The whole become today more and more complex and any undesirable event can have serious aftermath.

Current risks analysis methods lack elements to identify and characterize all the consequences of an unexpected event on a CI as well as its propagation to other CI.

So far, the concept of resilience appears as a key concept to bridge this gap. In that context, an evaluation model of the resilience based on a structured approach can give relevant information for managers and decision makers dealing with these undesirable events.

This article proposes an original approach to assess the resilience of a CI based on (1) the analysis of the resilience as a non-functional requirement, and (2) the use of a Digital Twin (DT) of the CI of interest, i.e., a numeric model of the whole system that describes the CI seen throughout various

dimensions, combined with simulation, evaluation and analysis mechanisms allowing to test the CI behavior face to different evolution scenarios. The studied CI in this paper is a Higher Education institution.

The next section focuses on the presentation and definition of the concepts of resilience, “-ilities” and resilience evaluation. The third section presents the main principles of the evaluation model of resilience based on 3 pillars and their articulation: modeling, digital twin and evaluation. Finally, the last section concludes this positioning paper and open perspectives.

2. Resilience and its evaluation model

2.1. Basic definitions

The concept of resilience and in particular its operationalisation can be very useful to help CI’s managers to make decisions to recover from an adverse event. It is used in many fields, each one using its one specific definition as illustrated in Table 1 [5].

<i>Field</i>	<i>Definition</i>
Material [6]	Capacity to stock energy and flexibility under a load without break off
Computer system [7]	Persistence of reliability facing modification or, incorporating reliability definition
Economy [8]	<ul style="list-style-type: none"> Dynamic resilience: speed of an entity or a system recover from an important shock to reach a wished state Static economic resilience: capacity of an entity or a system to maintain it function during a shock state

Table 1 Resilience definition by field

Despite the numerous definitions available in the literature, [24] gives a sufficient generic definition including the different dimensions of the resilience as “*the ability to anticipate, to be prepared for, to react, to adapt to disturbances and mitigate the consequences as well as to recover fast and efficiently also by the restoration and the preservation of services*”. Another definition gives the resilience as the “*capacity, for a system, to anticipate, to survive and to recover from a stress caused by a threatening situation*” [11].

To figure the abovementioned aspects, the following definition appears as one of the more relevant for us, *i.e.*, the capacity, for system to anticipate, to respond and to recover fast and efficiently from stress to a level of quality of service, performance and safety acceptable for the people.

Nevertheless, these different definitions highlight the importance of several capabilities to perform resilience as quality and safety). Therefore, we assume that other

capabilities to perform resilience may be relevant and of great interest, particularly resilience. Then, one of the goals of this work is to build a new definition of resilience, in relation with these other capabilities, and with regards to the dynamics of resilience.

2.2. Resilience dynamics

In risk management, resilience is defined through a three phases life cycle hereafter applied to a CI:

Anticipation highlights the capacity of the CI to avoid impacts of a disruptive event. It can be decomposed in two parts [5]. First the **Prevention** aims at preventing from the likeliest and the most predictable threats and trying to decrease the occurrences of the risk [5]; the **Preparation** (e.g., installation of safety barriers, safety protocols, crisis management resources, safety or failure strategies) [5].

Response phase is triggered when the system is impacted by the undesired event. The response phase mainly consists in following the emergency procedures or barriers and can be divided in two sub-phases [5]:

The **Absorption** phase highlights the endogenous capacity of the CI to reduce the negative impacts caused by disruptive events and to minimize its consequences with less efforts [19] [20]. This capacity can be improved during the preparation phase by increasing the system robustness or the system redundancy [19]. The absorption begins as soon as the event occurs and until the end of the initial and propagated effects of the event [5].

Adaptation phase highlights the capacity of the CI to adapt itself from the disruptive events via an auto-organization to minimize the consequences and try to control the situation to avoid an escalation. It can be improved via emergency systems (e.g., alarm) [19]. Adaptation is based on three fundamental concepts: 1) vulnerability to unpredictable stress, 2) the system potential to be modified, 3) the system flexibility [21]. The adaptation begins from the event apparition to the beginning of the recovery phase [5].

Lastly, the **Recovery** phase refers to the capacity of the CI to be repaired and restored quickly, if it is possible, to a normal and a reliable functioning mode. The QoS level of the CI has to be considered as acceptable by all CI’s stakeholders [19] [20] [5].

The challenge is to operationalize the resilience and to monitor it continuously, to characterize the best way a CI, before, during and after a catastrophic event. The proposed approach consists in applying some so-called model-based system engineering (MBSE) principles and tools to model the CI with a systemic approach and also by interpreting the resilience as a non-functional requirement to meet by the CI. By the principles of the MBSE, we want to build an evaluation model of the resilience based on non-functional requirements, which be applied and executed on a multi-view model of the CI.

2.3. Resilience assessment method: resilience as an ‘-ility’

Any system can be characterized by requirements expressing the capacity that the system must provide, or a

condition it has to fill to respond to a need of a stakeholder [22]. Two kinds of requirements are retained:

- Functional requirements, related to the functions the system must perform i.e., what it must do.,
- Non-functional requirements, related to other aspects of the system such as dimension, performance, interface... i.e., how it must do.

The resilience is clearly identified as a non-functional requirement and belongs to a class known as “-ilities” because most of requirements in this class end by -ility such as interoperability or maintainability [3][4].

In the frame of the analysis of “-ilities”, most research works focus on a specific requirement (e.g., reliability calculation). More recently, other works highlighted the possible relationships between different “-ilities”. Thus, [9] proposes a graph based on the analysis of papers from the literature and points up the co-occurrence between “-ilities”. The thicker the relationship, the more “-ilities” appear together in literature (figure 1).

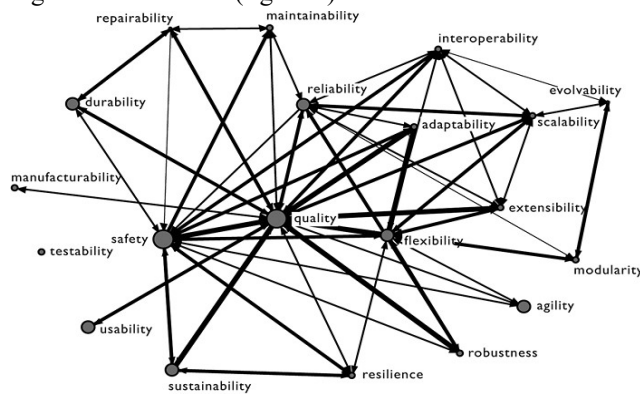


Figure 1 Correlation network of “-ilities” [9]

This graph shows for instance that resilience is related to sustainability, safety, quality and flexibility. It initiates the possibility to study a given “-ility” according to its relationship with other ones. However, his first approach must be improved to assess resilience. Indeed, first, some relations with other “-ilities” are missing as. For example, with security, adaptability or robustness. It is then required to establish clearly all the possible interactions and influences between the resilience and other “-ilities”. Second, the graph is based on the co-occurrence of “-ilities”. The nature of each relation remains not clearly identified and defined. [9] introduces the possible nature of substitution or compromise between “-ilities” but without specifying these ones and without identifying other possible natures. In that case, to develop a method to evaluate resilience, it is required to identify, define and formalize the possible nature of relationships between the resilience and other “-ilities”. Thanks to a relevant resilience centered graph and the formalization of the relations highlighted in this graph, it will be possible to get a reliable operator to evaluate the resilience. To sum up, an “-ilities” ecosystem may allow us to build a resilience evaluation model – i.e., composed of a set of “-ilities” that are in interaction.

2.4 Build a set of “-ilities”

The first step aims at identifying the different sets of “-ilities” available in the literature. Three main papers were consulted, the most complete lists of “-ilities” in the literature:

- Ross and al. (2011) [17], focuses on the identification of existing “-ilities”,
- Willis and al. (2011) [18], focuses on the identification of all existing “-ilities”,
- Moradi [5], focuses on the research of “-ilities” not identified in the two first.

The next step based on concatenating these three sets and withdrawing redundancies led to identify 101 “-ilities”.

A set of 101 “-ilities” is quite big to build an ecosystem of “-ilities”. In order to develop a set manipulable by end users, two rules, to reduce it, are defined.

Rule 1: The CI is a Higher Education institution, therefore, several “-ilities” applicable to computer system are removed from the initial set.

Rule 2: “-ilities” not well defined and very similar to others are removed from the initial set.

For example, Willis and al. identify the capability [18] and Ross and al. the process capability [17]. The first one is much better known than the second one. Therefore, only capability is kept on the list.

The goal is not to simplify the problem as much as necessary but to keep only a well-formed set of “-ilities” which is complete, without ambiguity and in which “-ilities” are well characterized. Therefore, applying these rules leads to a set of 70 “-ilities”.

2.5 Defining relation in the set

Building an eco-system of “-ilities” to support an evaluation model of the resilience, requires identifying the interactions between “-ilities” and their characteristics, (e.g., orientation, existence condition, and influence type). From the set defined, the relation between “-ilities” and resilience must be defined and formalized. Few methods are existing on the definition of the nature of the relation between “-ilities”. As above mentioned, [9] introduces the substitution and the compromise as existing relations. More recently, [5] develops a method to evaluate the resilience on the basis of the relation of influence (a variation of an “-ility” increases or decreases the resilience). However, other relations are proposed as:

- The **compensation** which represents an action to counterbalance, to balance, to neutralize something by something else. The compensation permits to balance an -ility effect by another -ility [5]. The source “-ility” (i.e., the one which will compensate another “-ility”) will reduce its value to compensate the target “-ility” (the “-ility” which necessitate a compensation).

- The **conflict** which is an opposition between -ilities. In the eco-system, the action of one can destroy another one [5].
- The **compromise**: which is an arrangement between two or more “-ilities” that make concessions to have a collaboration and to reach a majority. The compromise efficiency is based on the relaxation of a constraint [12].
- The **substitution**: is the replacement of one “-ility” by another “-ility”. The principle of substitution expresses the artifacts which have neutral effects. Their introduction in a system only has known effects but never has non-required effects [13]. The substitution permits to replace an object by another one, respecting the necessary characteristics of the replaced object.
- The **influence** is defined by the variation of an “-ility” resulting from the variation of another one [5]. This relation is well defined [5] [14] as an action, usually continuous, that exerts something on something else. It is defined by the variation of a target “-ility” by a source “-ility”. For example, we can consider that robustness has an influence on resilience. During the preparation or the absorption phases, the robustness can be seen as a protection barrier for our CI.

Some general illustrations of the relation are shown in the table 2.

Compensation	Sustainability compensates durability to support resilience
Conflict	Flexibility and robustness conflict with their relationship with resilience
Compromise	Robustness and sustainability can do a compromise to support resilience
Substitution	Reparability can substitute to maintainability to support resilience
Influence	Robustness influences positively the resilience, until a balance point

Table 2 Some illustration of the nature of relationships to consider between “-ilities”

Although these illustrations are easily understandable, there are not formalized to be used and integrated in an operator to evaluate the resilience. Thus, the next step is to define and clearly formalize these relations.

Next, the relationship can have an orientation. Between two “-ilities”, A and B, A can have an effect on B, but opposite cannot be necessary true. For this study, we choose to only take into account the effect of “-ilities” on resilience and not the opposite because the resilience is the key “-ility” to evaluate.

In the second paragraph of this paper, we discussed the life cycle of the resilience. This life cycle has an impact on the building of the eco-system. Indeed, some “-ilities” can be linked to another “-ility” in a particular phase of this life cycle, but this relationship can disappear during another phase. For example, the robustness has a relationship with the resilience during the sub phase preparation of the anticipation phase or during the sub phase absorption of the response phase. This relationship disappears during the sub phase prevention of the anticipation phase or the recovery phase.

This involves that there is one eco-system by phase or sub phase of the resilience’s life cycle.

4.3. Discussion

At this stage, the set of “-ilities” resilience centered is stabilized to 70. However, despites two hypotheses to split the problem and make the analysis easier, it is necessary to identify other mechanisms to reduce this set.

The formalization of the relations is still in progress in order to define a general operator to evaluate the resilience.

The following questions emerged:

- How to manage the loop of “-ilities”? (“-ility” A connected to B connected to C connected to A)
- The evaluation model of resilience is based on an eco-system of “-ility”, made of a set and relations. By their relations, these “-ilities” vary in relation to each other. To observe the evaluation, we may need an initial state of the eco-system. This initial state could be represented by a set of values for each “-ility” of the eco-system. This initial state will determine the veracity of the resulting value of resilience during the evaluation. How to build this initial state?
- How to formalize the relationships mathematically (compensation, substitution, compromise, conflict and influence)?

Once all these questions are resolved, we can build an evaluation model of the resilience, which will be performed by a Digital Twin.

3. Digital twin

3.1. Modeling of the CI and Digital Twin development

The evaluation model of the resilience will be performed by building and analyzing a global model of the CI. The choice is here to promote a systemic oriented and multi-views modeling approach highlighting at least functional, behavioral, organizational, and physical viewpoints of the CI [26]. The expected model is then represented as a Digital Twin (DT) of the CI, defined here as a “*digital model as representative as possible of a component or a system, feed by data to represent its environment and its operational conditions*” [16] (figure 2).

The DT is more and more used according to its numerous benefits. It allows to perform several types of operations

(test, verification, simulation, training...) without impacts of effects on the real system but staying as much as possible aligned and then ion coherence with this system. In that sense a DT is cost-effective (e.g., a modification requested following a test is less expensive by promoting then the notion of virtual prototype). It allows to test multiple running scenarios, to take care and analyze various possible evolutions of the system without being time consuming and involving several resources to coordinate and synchronize. As an example, in the case of the evaluation model of the resilience following a terrorist attack as an unexpected scenario, a DT representing building, and actors' behaviors and implementing scenario with simulation is more effective than playing the scenario in a real building with actors or at least complementary.

In the frame of the DT for the evaluation model of the resilience, the goal is to define all relevant views, associated modeling languages and extend them if these models must embed specific attributes that characterize the CI.

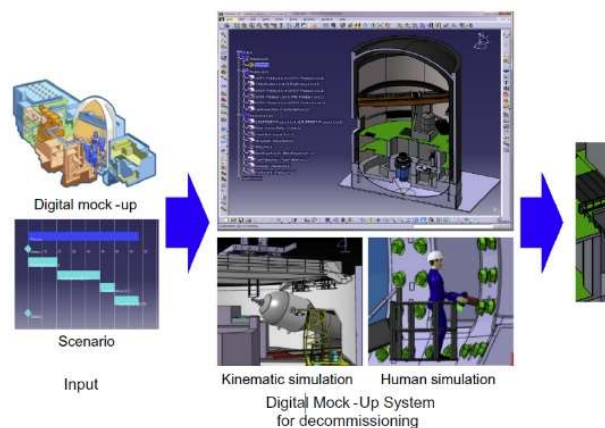


Figure 2 Example of a DT system for decommissioning of a nuclear plant

In the whole, the DT allows the manager to elaborate then test scenarios to understand their impacts on the resilience evolution. In the following section, the principle of modeling of the system and expectations concerning simulation of scenarios are presented.

The DT is hereafter based on the federation of models elaborated to describe the various viewpoints. A metamodel (MM) was realized to define and structure the concepts, attributes and relation between concept of the future models, these viewpoints and make appear modeling languages requested to elaborate these models. Indeed, a MM is composed of classes (corresponding to requested concepts e.g., buildings, actors, or processes), relations between classes e.g., an actor is involved in a process), and of attributes (e.g., actor's position and roles). These concepts and relations are structured in the different viewpoints and each viewpoint defines then what must be described in the model that corresponds to this viewpoint. Four viewpoints are needed to describe the CI: contextual, functional, behavioral and logico-organic viewpoints. More viewpoints can be added if necessary (to enrich the future

DT for instance and to allow the detailing or make more understandable a given aspect, configuration or situation that characterize the CI). Currently, we only focus on the four abovementioned viewpoints.

Last, one of the goals of the method is to allow a manager to monitor the CI considering the evaluation model of resilience. As representative as possible, the DT permits a better monitoring and visualization of the CI. Moreover, the DT permits to simulate as much scenarios as necessary to help the manager in his monitoring.

The following sections present all the view to include in the DT.

3.2. The contextual view

The contextual view aims to identify all systems that interact with the CI from different manners and evolve then at the interface of the CI. These interactions are modelled as services these systems provide to or expects from CI. The omission or addition of an interaction or an element that interact with the CI can lead of a lack of data or too much data to evaluate the resilience and lead to a wrong result and analysis for managers. Let's note that all the services are oriented (incoming or outgoing).

The figure 3 shows an example of a contextual view for a Higher Education institution (SOI). For the modeling of a terrorist attack, for instance, the model includes the police, the students, the staff, the assailant, etc...

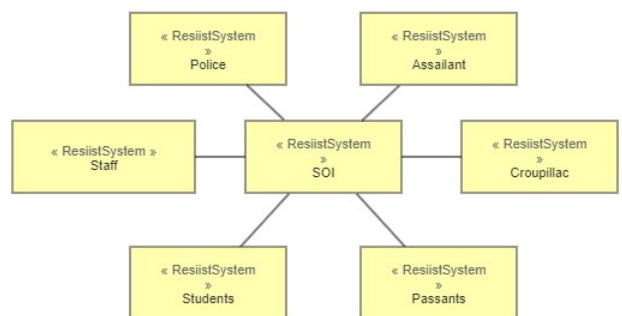


Figure 3 Example of a simplified contextual view for the CI

Last, each service provided by the CI allows us to identify more precisely what are then the expected functions of the CI, enriching then the functional viewpoint.

3.3. The functional view

The functional view describes and give an overview of the functional architecture of the CI, in terms of functions the CI must provide in order to satisfy both expected services functional requirements from CI's stakeholders but also expected scenarios such as the terrorist attack scenario. A function is often described as a process which is a sequence of activities. In our case, a process starts with a trigger event (an independent event or a process end).

Other information can be added on the functional view depending on the modeling language used and the purpose (key performance indicator, resource, time, processed object). The goal is to have a view of what is done, how it is done, when and by who. The figure 4 illustrates the

sequence of activities to evacuate a building. It is triggered by the event Alarm and 4 activities are done in sequence.

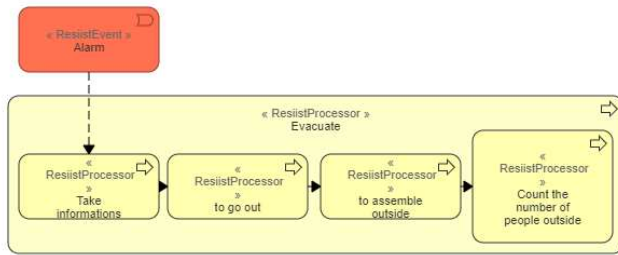
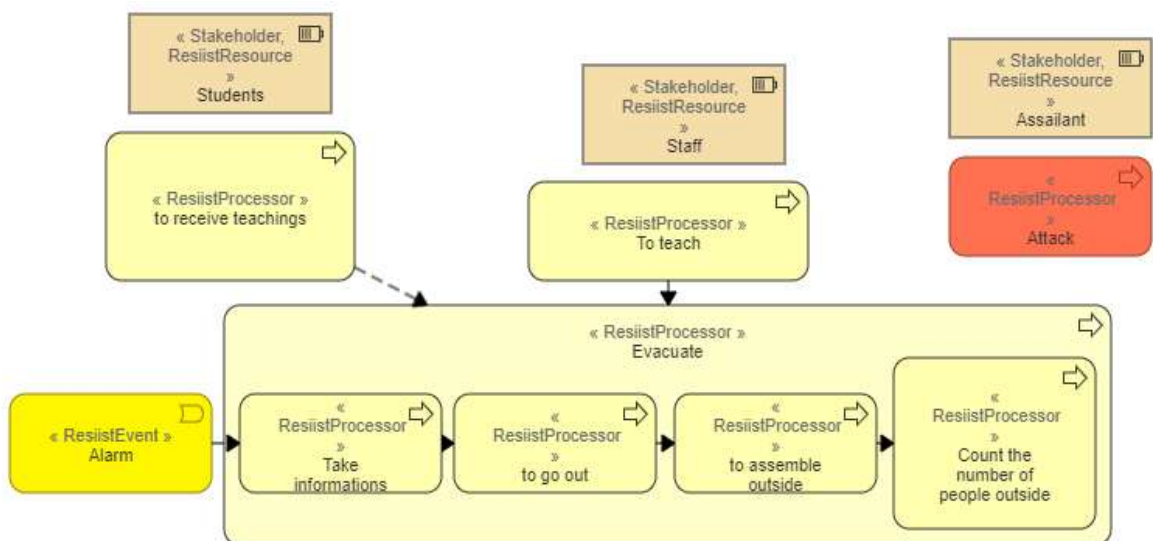


Figure 4 Example of a process in the functional view

3.4. The behavioral view

As the CI could be considered as a complex socio-technical system, its behavior has two scopes that are: 1) the description of the behavior of each process and 2) the description of the behavior of each actor who may be involved in these processes, the people in the building for instance. For example, during a lecture, the behavior of a teacher is to teach, he is standing up, in front of the class, describing something on the board. The students are sitting in front of the teacher, listening to the course. During a terrorist attack, the assailant is standing up or running, searching for victims. The students and the teachers are running to escape or moving squatting to not be spotted. Moreover, the process to evacuate occurs if assailants enter in the institution and this processor prevails on the processors giving a course and receiving a course (see figure 5). The figure 5 describes a scenario of teachers giving a course to students. An assailant is present in the building. As soon as the assailant enters the building and starts to attack (attack process in red), the alarm triggers (alarm event in yellow). Then, students and staff consider that respectively the process of listening to a lecture and the process of teaching are not even the priority and start the process of evacuation presented in the figure 4.

Figure 5 Example of a behavior of the CI



3.5. The physical view

The physical view describes the system in an organic, logic, topological or geographic point of view. GIS (Geographical Information System) tools or 3D models like BIM (Building Information Model) may feed the physical view. For our SOI, a 3D representation of the buildings is used.

All the four models described before provide static data for the evaluation model of resilience (e.g., wall resistance over fire).

3.6. Simulation

All the models described before, resulting of the different views of the system, aims at running simulations. The simulation has two goals, 1) to test the evaluation model developed, and 2) to help the managers to monitor the CI.

The simulation provides dynamic data for the evaluation model of the resilience (the unavailability of fire alarm during maintenance).

The simulation is possible with multi-agent systems (MAS). The MAS simulation of scenarios permits to make emerge the real behavior of the CI by assuming and considering then observing the evolution of each component of the CI putting in light the requested autonomy and relationships between these components (e.g., the self-evolution and proper decision-making process of a human actor that may then influence more or less another actor). Each agent corresponds then to a given concept highlighted in the Meta Model (MM) and its own behavior is modelled by evolution rules coming from the bibliography but no more detailed hereafter.

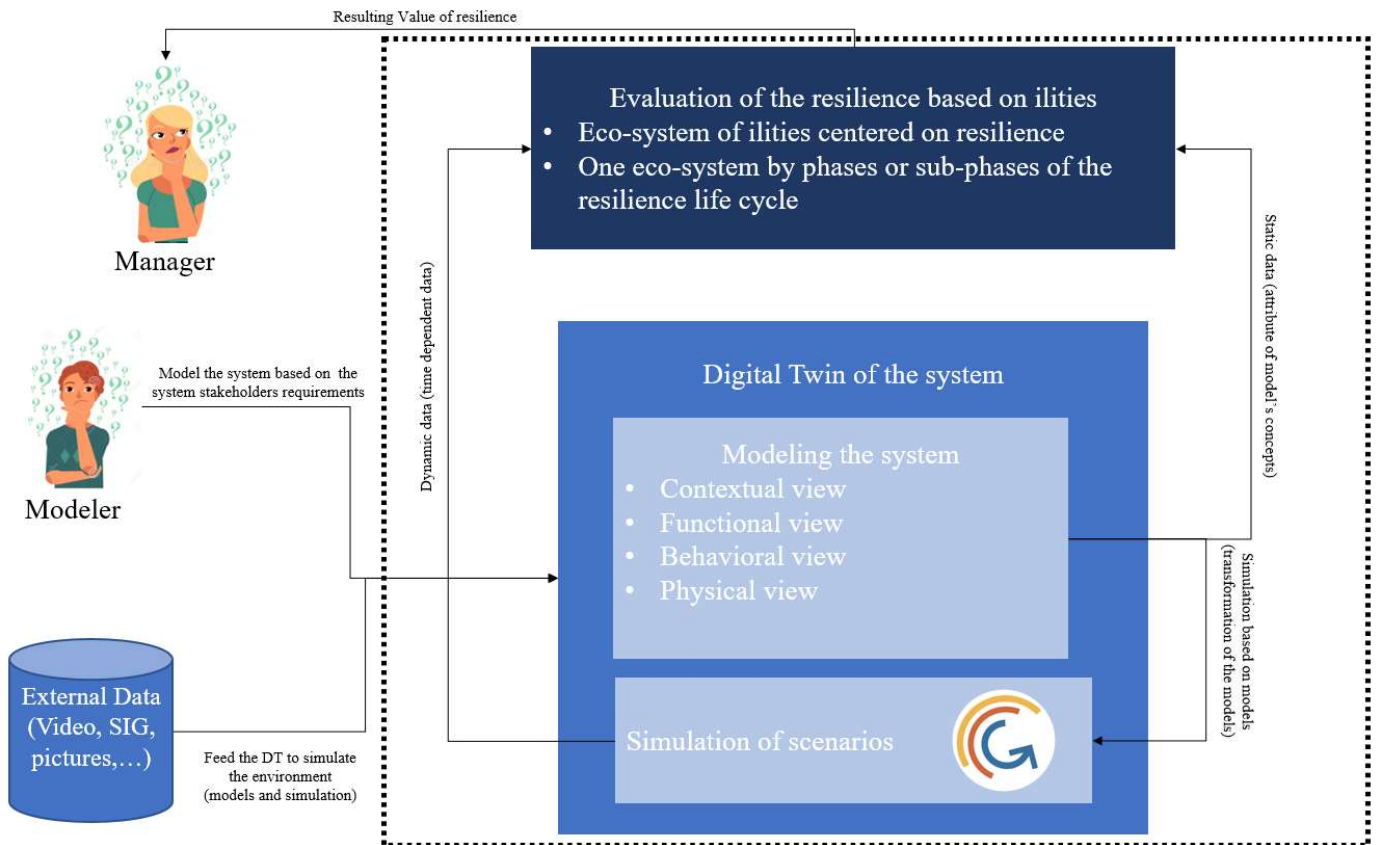


Figure 6 Components of the method and their articulation

3.7. Discussion about the DT

To simulate the environment and the operational conditions of the CI, external data must feed the DT. These data can come from different sources: video, GIS, database. Some of these data can be difficult to collect. Moreover, if we multiply the number of data sources, the synchronization of data can be an issue we will have to solve. If the collection of these data appears to be too difficult, it can be simulated. Moreover, a behavioral model of agent must be used to simulate the agent's behaviors. First, we want to test simulation with state machine to simulate the agent's behaviors, but a more complete model must be used to create a simulation environment as representative as possible of the reality.

One may ask how surprise (one principal characteristics of the crisis) is taken into account in the model. A specificity of multi-agent simulation lies in its ability to bring out emergent (in the sense of unforeseen) behavior. This kind of surprise event will enhance the experience of the manager of the CI to better face these situations. These new behaviors will enhance the experience of the end-user. However, it is not possible to model all the internal or external hazards that can affect a system. Therefore, it is possible that several situations remain unconsidered by the model, but it can be completed if necessary (as part of a learning process).

4. Conclusion

The method presented in figure 6 is under construction. Concerning the evaluation model of resilience, the set of “-ilities” have been built and may be reduced again with new rules. Moreover, even if the links between “-ilities” have been identified, they must be mathematically formalized now. Then, concerning the DT, the contextual, the functional and the organic models are already under finalization. The behavioral model must be improved, particularly about the agents' behavior to reach the most realistic behavior. When these two parts are finished, we will integrate the evaluation model of resilience to the DT, to test the method on scenarios. The integration will allow to adjust the evaluation model. Finally, this method, by the combination of an evaluation method of resilience and a DT of the CI of interest, method based on “-ilities” relations and simulation of scenarios, will permit to the manager to monitor efficiently his CI, with a good overview on each phase of the risk management: anticipation, response and recovery.

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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