Spatio-Temporal Graph for Improvement of Decision-Making in Risks Treatment

Mohamed Amine Messaoudi, Department of Computer Science, Université des Sciences et de la Technologie d'Oran Mohamed Boudiaf, USTO-MB, Oran, Algeria*

Latifa Dekhici, Department of Computer Science, Université des Sciences et de la Technologie d'Oran Mohamed Boudiaf, USTO-MB, Oran, Algeria & LAGEM Laboratory, Ecole Supérieure en Génie Électrique et Énergétique, Oran, Algeria

https://orcid.org/0000-0002-9581-6488

Myriam Noureddine, Department of Computer Science, Université des Sciences et de la Technologie d'Oran Mohamed Boudiaf, USTO-MB, Oran, Algeria

ABSTRACT

Failures that hinder the proper functioning of complex systems are characterised by frequencies of occurrence, rates of evolution, and variables periodicities. Indeed, a good design of this kind of system requires the elaboration of an adapted analysis and modelling approach, which takes into account the spatial-temporal dynamics of the systems elements dysfunction. This paper proposes a spatio-temporal modelling approach integrated into a risk management methodology. This modelling allows both to describe the evolution of the system in space and in time and to follow the spatial and temporal scope of a failure of the system in order to improve decision making in choosing the appropriate corrective action. The elements of the methodology are illustrated and validated by a case study of a wireless sensor network system.

KEYWORDS

Complex System, Corrective Action, Decision, Failures, Modeling Approach, Risk Management Methodology, Wireless Sensor Network

1. INTRODUCTION

System can be defined as a set of dynamic interacting elements that are highly integrated to accomplish an overall goal. Systems range from simple to complex, this complexity can be characterized by the high number of interactions between entities. This makes such systems difficult to model and not easily predictable. On the other hand, failures that affect the proper functioning of complex systems are characterized by varying frequency, rates of evolution and periodicity. Indeed, a good design of such systems requires the development of an appropriate analysis and modeling approach, which

DOI: 10.4018/IJDSST.303945

*Corresponding Author

supports the spatial and temporal dynamics of the functioning and the dysfunction of the components that make up these systems.

In this perspective, many works aimed to model complex systems and have been carried out by various authors (Aslani et al., 2020; Galli et al., 2020; Gouriveau et al., 2004; Nazeri et al., 2017; Latsou et al., 2019; Paul S.K et al., 2019; Weber et al., 2012) in order to enhance risk management techniques that identify, analyze and mitigate risks.

Considering the fast growth of system complexity, risk management must evolve its practices, modeling and design approaches, taking into account the spatial-temporal parameters that characterize the functioning and dysfunction of these kind of systems.

In this paper, a spatio-temporal modelling approach integrated into a risk management methodology is proposed to allow a dynamic visualization of the risk of failures events in complex system. This proposal uses connected graph of nodes and relationships with properties and labels. The objective is to provide the ability to display practical spatio-temporal information in order to improve decision making in choosing the appropriate risk treatment.

The spatio-temporal model should have the capacity to represent the behavior of the system and the evolution of its entities in time and space. Such a model should also detect the risks of failures and monitor their impacts not only at the local level, but also at a more global level.

The remainder of the paper is organized as follows. Section 2 reviews the literature on systems modelling in risk management. Section 3 presents the risk management methodology and the integrated spatio-temporal model and its characteristics. Section 4 is devoted to the description of model. A case of study is presented in Section 5 to verify the efðciency of the proposed model. Finally, some concluding remarks and suggestions for future research are provided in Section 6.

2. RELATED WORK

Several authors developed models for risk management, Gouriveau et al., (2004) defined a dependability analysis framework. They came up with a case tool dedicated to risk management knowledge based rules. Latsou et al., (2019) developed a methodology for the Petri Nets automated generation. Their methodology takes as its input a topology diagram with a complex system/process description that handle real life scenarios such as a large number of components/activities, control loops, dependent events, redundant and repairable components/activities. Their proposed methodology enables the detection of the critical components and design errors at an early design stage.

Nazeri et al., (2017) presented a fuzzy hybrid approach, including failure mode and effective analysis, decision-making trial and evaluation laboratory technique, and analytic network process. The aim was to select an appropriate maintenance policy through identifying the failures risk. The application was tested on tamping equipment in railway of Iran using a super matrix of weights and criteria as the failure risk.

A bibliographical review about the use of Bayesian networks over the 2000 to 2009 decade on dependability, risk analysis and maintenance was presented by Oliva et al., (2009). It has shown an increasing trend of the literature related to these domains. This trend is due to the benefits that Bayesian networks provide in contrast with other classical methods of dependability analysis such as Markov Chains, Fault Trees and Petri Nets. Another bibliographical review on the application of Bayesian networks to dependability, risk analysis and maintenance was presented by Weber et al. in 2012. This last review is based on an extraction of 200 specific references in dependability, risk analysis and maintenance applications among a database with 7000 Bayesian network references.

Till now, the risk management field still interests many researchers. Recently, Paul S et al., (2019) developed a recovery planning approach in a three-tier manufacturing supply chain, they considered several types of unexpected disturbances: demand fluctuation, and manufacturing disruptions and raw material supply. They used two steps mathematical formulations to model for a finite planning horizon the imperfect manufacturing while maximizing total profit then to schedule recovery. A heuristic was used to resolve the two mathematical models. Aslani et al., (2020) were attracted to risk measurement factor as reliability, acceptability and affordability of dynamic system. They developed a macro-level natural gas energy systems model to understand the complexity of the effective sub-systems o energy system with their related variables. Three scenarios were defined then analyzed to support decision makers. For other recent related works, one can refer to a review of risk management in System engineering in engineering management was given by Galli et al., (2020). The review focuses on the design and management of the system. They exanimated three models that help system engineers with making a complex system look simpler and less frightening: the Vee, Spiral, and Waterfall models.

Hence, researchers are more interested by dynamic systems. Furthermore, when it concerns dynamics systems, spatio-temporal aspect can interfere the system. Ciancia et al., (2016) combined statistical model checking, spatio-temporal logics, and simulation to model and analyse behaviour of bike sharing systems. They integrated those models and Markov renewal processes in tool-chain. Illic et al. (2020) aimed to manage uncertain disturbances, and particularly power imbalances, by optimizing available power resources. They centralized optimal control problem formulation of system-level performance objective subject to complex interconnection constraints and constraints representing heterogeneous internal dynamics of system components. They utilized an inherent multi-layered structure. For cost analyze, they use a bid function. Wentao et al., (2020) investigated spatio-temporal relational learning to model uncertainty-based accident anticipation. Their application concerned sequentially predicts the probability of traffic accident occurrence with dashcam videos and precisely on a Car Crash Dataset. They hybridized graph convolution and recurrent networks for relational feature learning, and leverage Bayesian neural networks to address the intrinsic variability of latent relational representations.

Hao Wang et al., (2020) studied Integrated Flood Risk Management methods in three aspects: identification of high-risk areas, assessment to quantify economic losses, and management to identify structural measures with the highest engineering benefits. These methods were applied to Beijing as a case study, and the results showed that the Zuoan-Road area was a high-risk area with economic losses over different return periods. Moreno-Cabezali and Fernandez-Crehuet (2020) studied risks associated with Additive Manufacturing R&D Project Management. A set of risks with a potential negative impact on project objectives are identified. The process is made by the measurement of two parameters: likelihood of occurrence and impact on project objectives. According to the responses of the experts, the level of relevance of each risk is calculated, innovatively, through a fuzzy logic-based model under Matlab. The proposed model prioritizes the risks that are more critical to develop appropriate response strategies. Oduoza (2020) developed a framework for risk management affordable and suitable for use especially by small and medium size enterprises in the manufacturing sector. Using a combination of Bayesian Belief Network (BBN) and Analytical Hierarchical Process (AHP) search algorithms, they identify key risk indicators that could undermine business performance (measured in terms of cost, time, quality and safety) from a system database, and thereby manage (monitor, identify, analyze, reduce, accept or reject their impact) them.

In literature, IT systems were investigated as a whole entity where risk management is applied.

Daza et al., (2018) focuses on factors that comprise effective risk communication, decision-making, and measurement of information technology (IT) and information assurance (IA) risk. They involve both IT/IA practitioners and recipients of risk communication through the identification of factors that influence IT/IA professionals. Prikladnicki et al., (2008) suggest the development of an integrated risk management process taking into account site dispersion. They report the results of an exploratory case study conducted in a software development center. Axelrod al., (2013) list a broad range of potential IT-related security risks and suggest how they might become exacerbated during times of economic stress. They offer recommendations for overcoming manageable hurdles and suggest how some risk reduction might be attained.

The term IT was sometimes linked to risk management. But IT was often considered as a tool to risk management in other fields.

Trajkovski et al., (2013) presents an overview of the proposed risk management framework and how it is designed to meet the challenges usually faced by IT-centric micro and small companies when implementing risk management. The segments covered by the framework include people, policy, methodology and process, and tools. Mühe et al., (2017) designed also an IT risk management framework for small and medium enterprises. The framework's objective was to provide an uncomplicated and accessible tool that combines essential elements from three leading (IT) risk management frameworks.

Risk management modeling in economic field assumes that dependent and independent parameters are both quantified and permanent, and that their relationships do not change neither in time nor in space. This makes it impractical when applied directly to an IT system due to the influence of external and internal factors, and the degree of impact between qualitative and quantitative variables. In other words, an IT system requires modeling that helps make entities more responsive to change. And it increases efficiency, reduces the risk of failures and optimizes the budget. And it also helps minimize the redundancy of certain data, making systems easier to integrate. But in general, risk management modelling in the economic field and for the process and organization are more present than those in the domain of manufacturing systems, and the spatio-temporal aspect has rarely appeared. Few researchers were interested in risk management modelling of IT systems.

In this paper, a spatio-temporal modeling is proposed approach integrated into a risk management methodology in order to allow a dynamic visualization of the risk of failures events in dynamic IT system. We rely on connected graph of nodes and relationships with properties and labels.

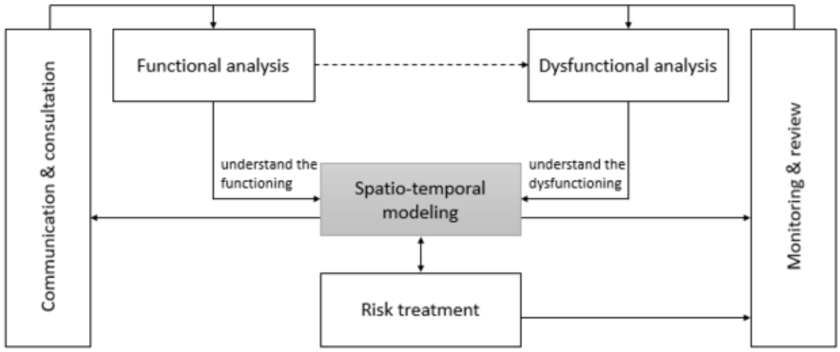
3. METHODOLOGY OF RESEARCH

The proposed methodology in this paper is based on the risk management process (IEC 31010: 2019). This methodology allows the merging of knowledge on the behavior of the complex system under study. Indeed, to model this type of system, it is necessary to include its functional and dysfunctional analysis, in order to develop a clear understanding of the risk of failure and to allow the selection of an appropriate risk treatment. Figure 1 below illustrates this methodology.

3.1 Functional Analysis

The first step is to perform a functional analysis to provide a good understanding of physical and functional structure of the system, the characteristics of the components of the system and the interactions between them, and the relationships between the system and its environment (Cole, 1998).

Figure 1. Methodology of research system



The methods used for functional system analysis can range from simple knowledge collection to well-structured methods such as FAST (Function Analysis System Technique) or SADT (Structured Analysis and Design Technique).

Functional analysis is essential to carry out a functional or material decomposition of the studied system. This decomposition provides broad perspective of the system's functions, leading to greater understanding of the overall system.

3.2 Dysfunctional Analysis

The functional analysis previously carried out does not bring information of the potential risks. It is thus necessary to complete it with a dysfunctional analysis, which allows to determine the principal causes of the dysfunction and also to specify the different states of the system.

The dysfunctional analysis is the overall process of risk identification, risk analysis and risk evaluation. The main methods considered at this level are Preliminary Hazard Analysis (PHA), Failure Modes, Effects and Criticality Analysis (FMECA) (Segismundo, 2008) and Fault Tree (FT).

3.3 Spatio-Temporal Modelling

The results of these two analyzes are pooled in a spatio-temporal modeling of the system that will represent it virtually before its realization, both in its expected functioning and in the failures likely to happen to it.

By studying this modeling, it becomes possible to validate or invalidate a technical solution, optimize architectural choices, replace critical components, this in order to:

- Minimize risks;
- Minimize operating costs;
- Tolerate, to the extent possible, certain errors by allowing operation in degraded mode under certain conditions;
- Allow the different stakeholders to communicate on a common basis.

3.4 Risk Treatment

Risk treatment involves selecting and agreeing to one or more correctives actions for changing the probability of occurrence, the effect of risks, or both, and implementing these options.

This is followed by a cyclical process of reassessing the new level of risk, with a view to determining its tolerability against the criteria previously set, in order to decide whether further treatment is required.

3.5 Monitoring and Review

As part of the risk management process, risks and controls should be monitored and reviewed on a regular basis to verify that:

- Assumptions about risks remain valid;
- Assumptions on which the risk assessment is based, including the external and internal;
- Context, remain valid;
- Expected results are being achieved;
- Results of risk assessment are in line with actual experience;
- Risk assessment techniques are being properly applied;
- Risk treatments are effective.

Accountability for monitoring and performing reviews should be established.

3.6 Communication and Consultation

Risk management should be inclusive. Appropriate and timely consultation and involvement of stakeholders enables their knowledge, views and perceptions to be taken into account which results in improved awareness and informed risk management and decision making.

4. MODEL DESCRIPTION

Spatio-temporal model is based on three concepts:

1. **Entities:** Defined as element of system with independent existence that can be differentiated from other elements, an entity is represented by a circle with a label.
2. **Relationships:** Defined as the association or interactions between entities.
3. **Functions:** They provide access information contained in the spatio-temporal model.

4.1 Time Modelling

The introduction of temporality at the model level is expressed through a specific scale on a straight line oriented (Figure 2), without beginning or end, to simulate the infinite dimension of the past and the future, in which a unit of distance is equal to a given amount of time.

The time axis can be used to visualize time intervals between events, durations and the simultaneity or overlap of events. The time values associated with these events can be queried at any time, the value returned is based on the selected instant (Ancona et al, 2001).

$\mathcal{T}$ is temporal domains and there is a finite set $T \in \mathcal{T}$ / $T = \{t1, t2, \ldots, tn\}$.

Let be a linear order over the set of time points in T with $ti<ti+1$ for $1<i<n$, the modelling conforms to the following temporal structures (Euzenat & Montanari, 2005):

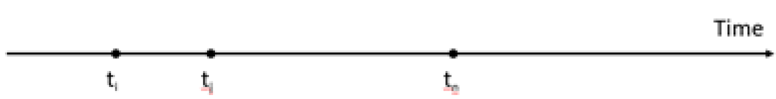
- Continuous T is isomorphic to the set of real numbers (this is the usual interpretation of time);
- Dense between every two different points there is a point:

$$\forall x, y \in T\ \exists z \in T\ (x < y \rightarrow x < z < y)$$

- Discrete every point having a successor (respectively, a predecessor) has an immediate one:

$$\forall x \in T\ ((\exists y \in T\ (x < y) \rightarrow \exists z \in T\ (x < z \wedge \forall w \in T\ \neg(x < w < z))) \wedge$$
$$(\exists y \in T\ (y < x) \rightarrow \exists z \in T\ (z < x \wedge \forall w \in T\ \neg(z < w < x))))$$

Figure 2. Time Axis



4.2 Relationships Modelling

4.2.1 Spatial Relations

A spatial relation specifies how some entity is located in space in relation to some reference entity. Commonly used types of spatial relations are *topological*, *orientation* and *distance* relations (Clementini, 2019). Topological relations describe whether two non-disjoint entities intersect or not, and, in the former case, how they intersect (Randell et al, 1992; Mark, 1999). Orientation relations describe where entities are placed relative to one another (Cohn & Hazarika, 2001). Distance relations may be pure Euclidean distance or may be given in qualitative rather than metric terms (Mark, 1999). The choice for specific spatial relations is strongly related to the context of their use.

Modelling spatial relations:

- T is time axis / T= {*t1, t2, t3, …, tn*}
- X(*t*) a set of entities at a point of time *t*
- *a* and *b* two entities ∈ X that exist at the same time *t*
- If *a* and *b* are in spatial relation ρ_s then: $a\ \rho_s\ b$

4.2.2 Spatio-Temporal Relations

Spatio-temporal relations can be defined as spatial relation holds for an interval, that is, relation holds for a certain time interval, and it does not change (Salamat & Zahzah, 2012). A spatiotemporal relationship always exists between two different times (Aydin & Angryk, 2018).

Modelling spatio-temporal relations:

- *a* and *b* two entities ∈ X that exist respectively at time ti and tj with ti < tj.
- If the space associated with spatial entity *b* is in spatial connection relationship ρ_s with that of *a* then there is a spatio-temporal relationship between these two entities: $a_{ti}\ \rho_{st}\ b_{tj}$ (Del mondo et al, 2012).

4.2.3 State Relations

State relation describes the state of an entity when it performs a normal function during a time interval; there are three states relations: continuation, irregularity and derivation relations:

1. **Continuation relations:** If there is continuation relation β between the same entity at different times, it means that the entity continues its normal functioning during this time interval.
2. **Irregularity relations:** If there is Irregularity relation γ between the same entity at different times, it means that the entity is irregular in its operation during this time interval.
3. **Derivation relations:** If there is derivation relation δ between entities at different times, it means the functioning of this entity has been modified by adding or removing of components, it can also be the result of combination between two entities.

4.3 Model Functions

These functions are defined on the relationships described above; they allow access to the information contained in our modelling (Del mondo et al, 2012).

Let: x be a spatial entity and X the set of spatial entities.

t a moment in the T axis (Time):

1. Spatial neighborhood function:

$\rho_s(x) = \{y \in X / x\ \rho_s\ y\}$

This function returns the set of spatial neighbors of x.

2. Spatial neighborhood function (at d distances):

$\rho_s^d(x) = \{y \in X / x\ \rho_s^d\ y\}$

This function returns the set of spatial neighbors of x which are at d steps.

3. Spatiotemporal neighborhood functions:

$\rho_{st}^+(x) = \{y \in X / x\ \rho_{st}\ y\}$

This function returns the set of spatio-temporal neighbors of x at time t + 1.

$\rho_{st}^-(x) = \{y \in X / y\ \rho_{st}\ x\}$

This function returns the set of spatio-temporal neighbors of x at time t – 1.

4. Spatiotemporal neighborhood functions (at i intervals):

$\rho_{st}^{+i}(x) = \{y \in X / x\ \rho_{st}^i\ y\}$

This function returns the set of spatio-temporal neighbors of x at +i intervals.

$\rho_{st}^{-i}(x) = \{y \in X / y\ \rho_{st}^i\ x\}$

This function returns the set of spatio-temporal neighbors of x at -i intervals.

5. States functions:

$\rho_{state}^+(x) = \{y \in X / x\ \rho_{state} y\}$

This function returns an entity in relation of state with x (the future of x at one interval).

$\rho_{state}^-(x) = \{y \in X / y\ \rho_{state} x\}$

This function returns an entity in relation of state with x (the past of x one interval).

$\rho_{state}^{+d}(x) = \{y \in X / x\ \rho_{state} y\}$

This function returns an entity in relation of filiation with x (the future of x at +d intervals).

$\rho_{state}^{-d}(x) = \{y \in X / y \, \rho_{state} x\}$

This function returns an entity in relation of filiation with x (the past of x at -d intervals).

ρ_{state} can be replaced by β, γ or δ.

6. Failures Detection (FD).

   Let: x a spatial entity and X the set of spatial entities.
   t an instant in the interval T (Time):

$\forall x \in X$ and $\forall t \in T$
FD: X * T {true, false}
FD (x, t) = {true if $x \notin \rho_{state}^{+}(x)$, else false}

5. CASE STUDY

In this section, the authors present the methodology of risk management applied to a network of wireless sensors whose nodes are of type "LLN" (Low-power and Lossy Network). The methodology is centered around a spatio-temporal modelling which takes into account all the functional interactions between the nodes of the network, as well as their behavior in the event of failure, with a view to proposing an appropriate corrective action.

The first part introduces the functional and dysfunctional analysis of the system to meet the requirements of modelling. The second part proposes the spatio-temporal model corresponding to the studied LLN, the inputs and outputs of this model are validated by a simulation with Cooja.

5.1 Functional and Dysfunctional Analysis

Although SNs vary greatly in terms of their capabilities (e.g., processing power, battery capacity), there are four fundamental components that are common in all SNs: a sensing unit(s) or simply sensor(s), a radio unit or transceiver, a processing and memory unit or processor, and a power unit or battery, as shown in Figure 3. The sensor is responsible for the translation of physical phenomena detected/measured in the region of interest (RoI) to electrical signals. The transceiver enables the SN to communicate wirelessly with its neighboring SNs and with the sink node. The processor is responsible for performing all required computations and controlling both the sensor and transceiver. The battery supplies all three components with power (Deif & Gadallah, 2017). There are some other sub-units that are application dependent.

Figure 4 illustrates graphically a decomposition of the studied system, there are three main sub-systems and each sub-system is decomposed into components.

In the context of risk management (Herrmann, 2015), the FMEA process first identifies the failure modes for the components. This activity is risk identification. The process continues by determining, for each failure mode, the probability that it will occur (occurrence), the probability that it will not be detected if it occurs (detection), and the consequences on the component and on the complete system if it occurs and is not detected (severity). This activity is a type of risk analysis. Typically, these three factors (the severity, the occurrence, and the detection) are combined to get an overall risk priority

Figure 3. Wireless Sensor Network (WSN)

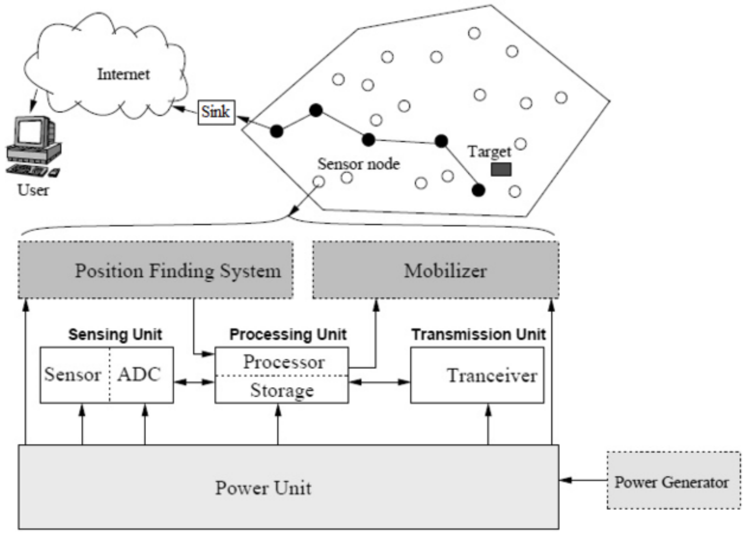
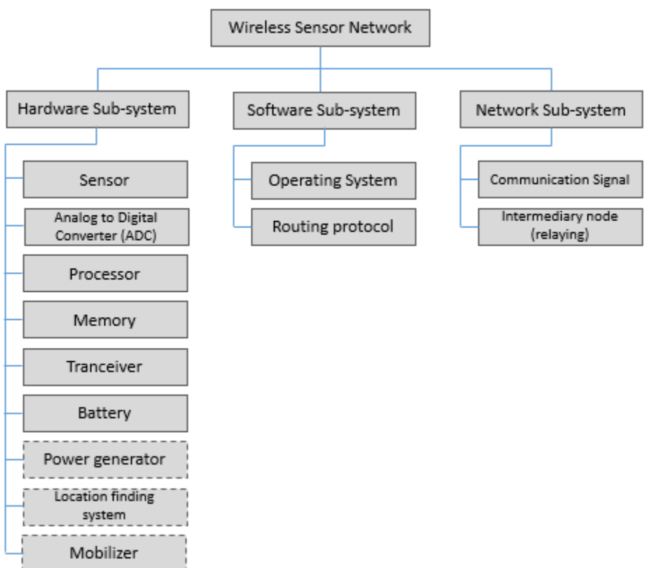


Figure 4. Functional decomposition of Wireless Sensor Network



number (RPN), and those failure modes with RPNs that are too large need to be addressed (treated) if possible (cost and other attributes need to be considered as well). This activity is risk evaluation.

Based on the functional analysis and the functional decomposition of WSN, the authors apply the FMEA approach which consists in:

- Search for failure modes, the focus here is on how the function can fail.

- Search for causes, in fact a cause is the initial anomaly that can lead to the failure mode. In this phase, an exhaustive search must be made for the causes that may trigger the potential appearance of the failure mode.
- Study the effects, each failure mode causes an effect, i.e. there is a consequence on the function.
- The relative risk of a failure and its effects is determined by three factors:
  - Occurrence (O), is the probability or frequency of the failure occurring.
  - Severity (S) is the consequence of the failure should it occur.
  - Detection (D) is the probability of the failure being detected before the impact of the effect is realized.

Each of these three factors is based on a 10-point scale, with 1 being the lowest ranking and 10 the highest (Mikulak et al, 2017).

- Calculate the risk priority number, or RPN, which equals O × S × D. The RPN (which will range from 1 to 1,000 for each failure mode) is used to rank the need for corrective actions to eliminate or reduce the potential failure modes, the authors decide that any RPN above 200 creates an unacceptable risk.

Two examples of FMEA grids are shown in Table 1 and Table 2.

The use of FMEA allowed the authors to confirm there are several failures that can affect the reliability of a LLN by compromising its functionality in terms of coverage and/or connectivity. These failures are factors pertinent to the functionality of the deployed SNs, mainly, SN power failure, hardware failures, and software failures.

5.2 The Proposed Model

In this section, the authors illustrate how to realize spatio-temporal graph $G_{st} = (X_t, E)$ of wireless sensor network system, where X_t represents the graph nodes at time t and E represents the graph edges that are relations. As shown in Figure 5, X_{t1} is composed of 12 nodes (1 sink node and 11 sensor nodes) observed at four consecutive times T= {*t1, t2, t3, t4*}. The details of each time are described as follows.

- **At time t1:** Initially all the sensor nodes working properly, an edge (spatial relation) exists between two nodes when corresponding sensors are located within the communication range of each other.
- **At time t2:** Failure Detection FD (node 9, t2) = {true} because node 9 Ï ρ_{state}^{+} (node 9) means that node is considered as failure sensor node.

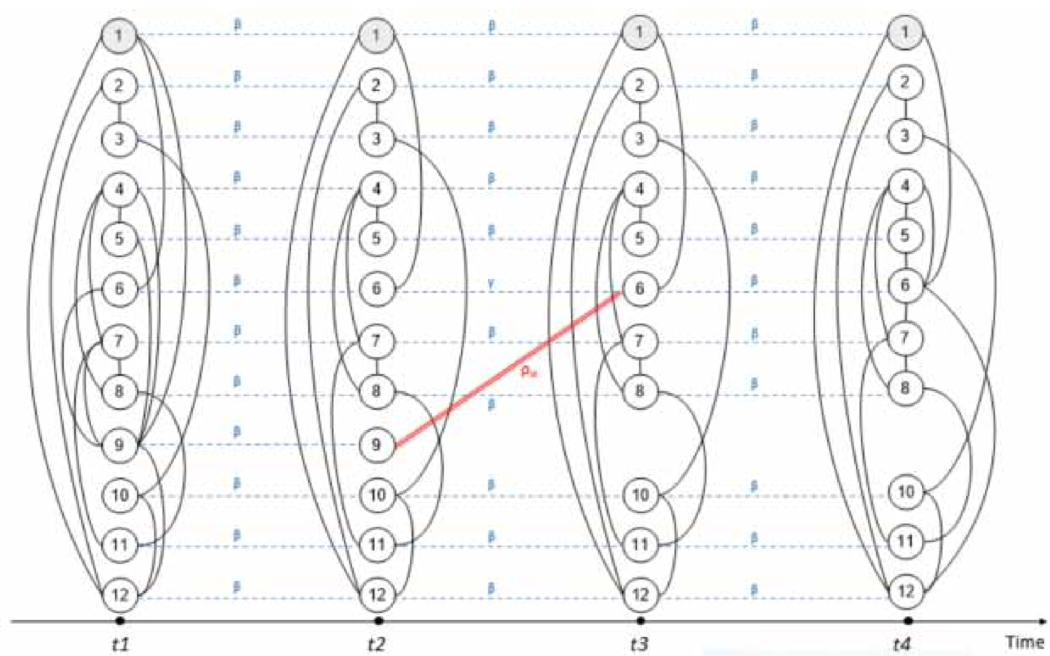
Table 1. Example 1 FMEA of processor component

System: LLNs Networks Sub-system: Node Sensor Hardware					Risk Priority Number (RPN) and Nominal Indices			
Component	**Functions**	**Failure Modes**	**Failure Causes**	**Failure Effects**	**Occurrence O**	**Severity S**	**Detection D**	**Risk Priority Number**
Processor	Performs data processing operations and communications protocols	Does not function	Battery depletion	Node failure	7	8	8	448
		Does not function	Physical damage	Node failure	6	8	8	512
		blocking	Incorrect input data	Node failure	8	8	9	576

Table 2. Example 2 FMEA of battery component

System: LLNs Networks Sub-system: Node Sensor Hardware					Risk Priority Number (RPN) and Nominal Indices			
Component	**Functions**	**Failure Modes**	**Failure Causes**	**Failure Effects**	**Occurrence O**	**Severity S**	**Detection D**	**Risk Priority Number**
Battery	Allows electrical energy to be stored in chemical form and released as direct current	Does not supply energy	Physical damage	Node failure	7	8	7	392
		Does not supply energy	Battery depletion	Node failure	7	8	8	448
		Internal or external leakage	Short circuit or internal crack	Battery depletion	6	8	7	336
		Intermittent operation	Insufficient load	Node failure	7	8	7	392
		Rapid discharge	Normal wear	Node failure	7	8	7	392

Figure 5. Spatio-temporal modelling



- **At time t3:** After failure detection with FD, the corrective action proposed in this paper allows at the first time, to calculate the number of links transiting through a failed node, this indicator measures the importance of the node whose failure reduces the overall connectivity of the network. In the second step, the solution is focused to replace the failure node by closest mobile node with a low degree of importance (low betweenness centrality).

Algorithm 1. Corrective Action algorithm

```
Corrective_Action_Algorithm
Input: Gst(X_t,E), RTL: risk tolerance limit,
Begin
  Foreach t ∈ T ∧ Foreach x_i ∈ X_t
    If FD(x_i,t) = true then
      If  ∪^k_{d=1} ρ_s^d <= RTL then
      Choose a node y ∈ X_t with low betweenness centrality
      Do x_i ρ_st y at time t+1
      End
    End
End
```

- **At time t4:** The failure of the critical node 9 causes the partitioning of the network, the corrective action that consists in the node 6 moving towards the position of the node 9 which will allow to restore the network connectivity at t4.

5.3 Model Validation

Model validation is performed by comparing the results obtained by the proposed spatio-temporal modelling with those of the real system simulation. In order to ensure that spatio-temporal model correctly represents the real system.

The Contiki OS based COOJA Network simulator is used to demonstrate that the behavioral data generated by the spatio-temporal model are the same data that characterize the real system.

5.3.1 Simulation Parameters

The wireless sensors network deployed in an area of 200×150 m^2 is considered. The locations of the sensor nodes are fixed and a priori known, in such a way that all spatial relations of the space-time model exist. Table 3 summarizes the most important parameters of the simulation

In the following, we precise the adopted assumptions:

1. All nodes are mobile.
2. All nodes are homogeneous.
3. The sensors monitoring zone is assumed without obstacles.
4. Only one failing node at a time.

5.3.2 Typical Scenarios

First scenario (Sc_1) simulation of the system in normal operation to establish a reference state, the second scenario (Sc_2) simulation of a failure where the undesirable event occurs, i.e. the loss of a critical node, the third scenario (Sc_3) is the simulation represented by the spatio-temporal model, which consists of triggering the corrective action when one of the critical nodes no longer functions correctly. So the authors present with these simulations the behavior of the system in three states: functional state, failure state and failure state with correction.

5.4 Result and Discussion

Effectiveness of the proposed model is shown by the simulation results.

Table 3. Simulation parameters

Settings	Values
Operating system	Contiki 2.7
Simulator	Cooja
Simulation duration	1200s – 1260s
Nodes position	Random
X; Y area	200m x 150m
TX range	100m
Routing protocol	RPL
Objective Function	Objective Function 0 (OF0)
Mote Type	Sky mote
Node count	11 + sink
Mobility model	Way point
Radio environment	UDGM(Distance Loss)

The IPv6 Routing Protocol (RPL) was standardized as routing protocol to meet the requirements of Low-power and Lossy Networks (LLNs) applications. RPL organizes a network as a Destination-Oriented Acyclic Graph (DODAG) rooted at the sink node, the expected transmission count (ETX) metric, is a measure of the quality of a path between two nodes in a wireless packet data network. Figure 6 shows the construction of the DODAG according to the third scenario, at time t1 all the sensor nodes working properly, at time t2 failure of a critical node and the network lost connectivity with 6 nodes, at t4 connectivity is restored with 5 nodes after the corrective action is executed.

Figure 7 shows the results of the comparison between the three scenarios according to the number of connected nodes and received packets, we can observe how the simulation results, especially the third scenario, confirm that the proposed model better reflects the reality.

Scenario 1: This first simulation aims at showing the good functioning of the WSN network during a reasonable period of time t=[0-1300]seconds, this scenario constitutes a basic reference for the other scenarios, indeed the DODAG is built after approximately 100 seconds and the whole of the 12 nodes which constitute the network are connected as shown in the following figure, during this period none of the nodes breaks down and the connectivity of the network is evaluated at 100%, and the average of the received packets during this period is 10.15 as shown in the (Sc_1) in figure 7.

Figure 6. The construction of the DODAG according to the third scenario

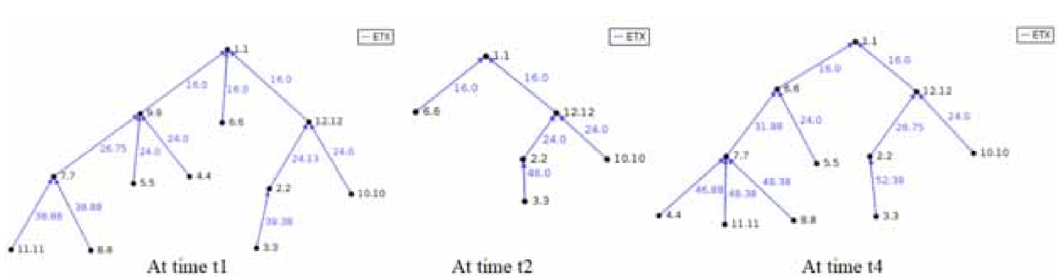
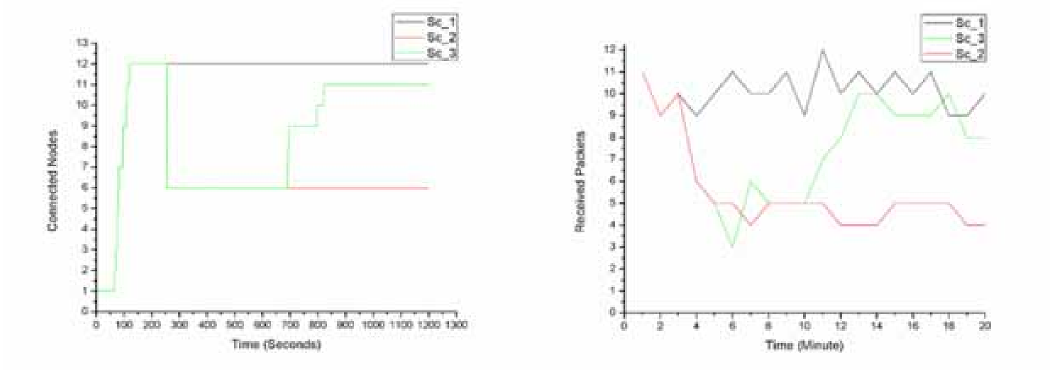


Figure 7. Comparison between the three scenarios



Scenario 2: Is the simulation of a failure where the undesirable event occurs, i.e. the loss of a critical node, at t=250 seconds node 9 fails without any corrective action, the authors then note that the network loses connection with 5 other nodes. In terms of percentage of connectivity, there is a 50% loss of connectivity compared to the first scenario. At the end of this topology with only 6 nodes, the average received packets is estimated to be 5.52 as well illustrated in the figure 7 (Sc_2). This result is not satisfactory and forces to redesign the network in case of a failure of a critical node.

Scenario 3: Is the simulation represented by the space-time model. This time, unlike the previous scenario, a corrective action is triggered when a critical node fails. Figure 7 (Sc_3) shows the connectivity status of the network, with connections to the lost nodes gradually being established to reach a total number of 11 nodes after the corrective action is triggered, i.e. an estimated connectivity of 91.66%. The authors note notable topological changes compared to the connections established in the 2nd scenario and the average number of packets received is estimated at 7.78.

According to the proposed model which gives an overall vison of the complex system with its spatial and temporal parameters. Thus, the authors obtain a simple and understandable presentation of WSN, even in the event of a malfunction. The use of the model's concepts allows to extract the most useful spatial features and capture the most essential temporal features coherently. In addition, the model has shown that it can be used for Improvement of decision-making in risks treatment through the detection and correction of failures in time in order to guarantee a high availability of the system. The results of the simulations confirm this, as after the failure of node 9 the network lost connectivity with 6 nodes but the execution of the corrective action allowed to recover 5 nodes.

6. CONCLUSION

The work described in this paper a spatio-temporal modeling approach integrated into a risk management methodology. A representative case study from the Wireless Sensor Network system implemented the methodology. This complex system is composed of a distributed set of interacting entities (sensors nodes).

In the beginning, to establish a more reliable spatio-temporal model of the system, the authors carried out a double analysis (functional and dysfunctional). The use of the failure mode and effects analysis (FMEA) as a method for assessing risks helped identify and quantify the influence of a possible system failure.

Afterward, Spatio-temporal modeling in the form of a graphic design is proposed, it makes it possible to apprehend the complexity of the system by representing the numerous entities that compose it as well as the relations which they maintain between them, this modeling makes it possible to project the system dynamics in space and time and to test a wide variety of hypotheses (temporal evolution of entities, influences of different factors, the scope of a failure, the identification of an undesirable event).

Finally, to validate the modeling, simulations were realized on various scenarios of system operation and dysfunction. Thus, the COOJA simulator was used to simulate a particular type of wireless sensor networks (LLN's) based on the proposed spatio-temporal model. These simulations make it possible to ensure by comparison that the spatio-temporal model represents the real system. They are also used to assess the strategies to be followed in the event of a failure of a critical node, thus enabling the quality of the corrective actions to be validated against the feared malfunction scenarios.

This study accordingly presents a promising spatio-temporal modeling approach integrated into a risk management methodology that allows a dynamic visualization of the risk of failures events within a complex system. As well as providing the ability to display practical spatio-temporal information in order to improve decision making in choosing the appropriate corrective action which can help to deal with dysfunction situations in a more elaborate manner.

However, some outstanding issues still need to be addressed. As an example, the proposed modelling can be subjected to spatial and temporal granularity constraints allowing to visualize and analyze the system at different levels of detail. The consideration of this granularity is not addressed in this proposal.

As the future work of this study, new case studies of various complex systems need to be experimented with the presented methodology. The spatio-temporal model can be further reinforced by concepts and additional semantics when the dysfunctional behavior of the system is difficult to apprehend. Finally, the simulation results can be enriched by including reliability evaluation taking into account the failure rate correlation.

FUNDING AGENCY

This research received no specific grant from any funding body in the public, commercial, or not-for-profit sectors.

REFERENCES

Ancona, D. G., Okhuysen, G. A., & Perlow, L. A. (2001). Taking time to integrate temporal research. *Academy of Management Review*, *26*(4), 512–529. doi:10.5465/amr.2001.5393887

Aslani, A., Akbari, S., & Tabasi, S. (2018). The Robustness of Natural Gas Energy Supply: System Dynamics Modelling. *International Journal of System Dynamics Applications*, *7*(3), 57–71. doi:10.4018/IJSDA.2018070103

Axelrod, C. W., & Haldar, S. (2013). Security Risks to IT Supply Chains under Economic Stress. *International Journal of Cyber Warfare & Terrorism*, *3*(4), 58–73. doi:10.4018/ijcwt.2013100107

Aydin, B., & Angryk, R. A. (2018). Modelling Spatiotemporal Relationships Among Trajectories. In *Spatiotemporal Frequent Pattern Mining from Evolving Region Trajectories. SpringerBriefs in Computer Science*. Springer. doi:10.1007/978-3-319-99873-2_3

Bao, W., Yu, Q., & Kong, Y. (2020). Uncertainty-based Traffic Accident Anticipation with Spatio-Temporal Relational Learning. In *Proceedings of the 28th ACM International Conference on Multimedia* (pp. 2682-2690). doi:10.1145/3394171.3413827

Ciancia, V., Latella, D., Massink, M., Paškauskas, R., & Vandin, A. (2016). A tool-chain for statistical spatio-temporal model checking of bike sharing systems. In *International Symposium on Leveraging Applications of Formal Methods* (pp. 657-673). Springer. doi:10.1007/978-3-319-47166-2_46

Clementini, E. (2019). A Conceptual Framework for Modelling Spatial Relations. *Information Technology and Control*, *48*(1), 5–17. doi:10.5755/j01.itc.48.1.22246

Cohn, A. G., & Hazarika, S. M. (2001). Qualitative spatial representation and reasoning: An overview. *Fundamenta Informaticae*, *46*(1-2), 1–29.

Cole, E. L. (1998). Functional analysis: A system conceptual design tool and application to ATC system. *IEEE Transactions on Aerospace and Electronic Systems*, *34*(2), 354–365. doi:10.1109/7.670319

Daza, R., & Hargiss, K. M. (2018). Factors Comprising Effective Risk Communication, Decision-Making, and Measurement of IT and IA Risk. *International Journal of Strategic Information Technology and Applications*, *9*(1), 23–40. doi:10.4018/IJSITA.2018010102

Deif, D., & Gadallah, Y. (2017). A comprehensive wireless sensor network reliability metric for critical Internet of Things applications. *J Wireless Com Network*, *145*(1), 145. Advance online publication. doi:10.1186/s13638-017-0930-3

Del Mondo, G., Stell, J. G., Claramunt, C., & Thibaud, R. (2010). A Graph Model for Spatio-temporal Evolution. *Journal of Universal Computer Science*, *16*(11), pp1452–pp1477. doi:10.3217/jucs-016-11-1452

Euzenat, J., & Montanari, A. (2005). Time granularity. In Handbook of temporal reasoning in artificial intelligence. Elsevier. doi:10.1016/S1574-6526(05)80005-7

Galli, B. J. (2020). Application of Systems Engineering to Risk Management: A Relational Review. *International Journal of System Dynamics Applications*, *9*(2), 1–23. doi:10.4018/IJSDA.2020040101

Gouriveau, R., & Noyes, D. (2004). Risk management–dependability tools and case-based reasoning integration using the object formalism. *Computers in Industry, 55*(3), 255-267. 10.1016/j.compind.2004.08.003

Herrmann, J. W. (2015). *Engineering decision making and risk management*. John Wiley & Sons.

Ilic, M., & Jaddivada, R. (2020). Unified value-based feedback, optimization and risk management in complex electric energy systems. *Optimization and Engineering*, *21*(2), 1–57. doi:10.1007/s11081-020-09486-y

International Electrotechnical Commission. (2019). *Risk Management–Risk Assessment Techniques. IEC 31010: 2019*. International Electrotechnical Commission.

Latsou, C., Dunnett, S., & Jackson, L. (2019). A new methodology for automated Petri Net generation: Method application, *Reliability Engineering & System Safety*, *185*, 113-123. 10.1016/j.ress.2018.12.017

Mark, D. M. (1999). Spatial representation: A cognitive view. *Geographical information systems: Principles and applications, 1*, 81-89.

Mikulak, R. J., McDermott, R., & Beauregard, M. (2017). *The basics of FMEA*. CRC Press.

Moreno-Cabezali, B. M., & Fernandez-Crehuet, J. M. (2020). Application of a fuzzy-logic based model for risk assessment in additive manufacturing R&D projects. *Computers & Industrial Engineering, 145*, 106529. 10.1016/j.cie.2020.106529

Mühe, S., & Drechsler, A. (2017). Towards a Framework to Improve IT Security and IT Risk Management in Small and Medium Enterprises. *International Journal of Systems and Society*, *4*(2), 44–56. doi:10.4018/IJSS.2017070104

Nazeri, A., & Naderikia, R. (2017). A new fuzzy approach to identify the critical risk factors in maintenance management. *International Journal of Advanced Manufacturing Technology*, *92*(9), 3749–3783. doi:10.1007/s00170-017-0222-4

Oduoza, C. F. (2020). Framework for Sustainable Risk Management in the Manufacturing Sector. *Procedia Manufacturing, 51*, 1290-1297. 10.1016/j.promfg.2020.10.180

Oliva, G. M., Weber, P., Simon, C., & Iung, B. (2009). Bayesian networks applications on dependability, risk analysis and maintenance. *IFAC Proceedings Volumes, 42*(5), 215-220. 10.3182/20090610-3-IT-4004.00042

Paul, S., Sarker, R., Essam, D., & Lee, P. T. W. (2019). Managing sudden disturbances in a three-tier manufacturing supply chain: A mathematical modelling approach. *Annals of Operations Research*, *280*, 299–335. doi:10.1007/s10479-019-03251-w

Prikladnicki, R., Evaristo, R., Audy, J. L., & Yamaguti, M. H. (2006). Risk Management in Distributed IT Projects: Integrating Strategic, Tactical, and Operational Levels. *International Journal of e-Collaboration*, *2*(4), 1–18. doi:10.4018/jec.2006100101

Randell, D. A., Cui, Z., & Cohn, A. G. (1992). A spatial logic based on regions and connection. KR, 92, 165-176.

Salamat, N., & Zahzah, E. H. (2012). Spatio-temporal reasoning by combined topological and directional relations information. *International Journal of Artificial Intelligence and Soft Computing*, *3*(2), 185–201. doi:10.1504/IJAISC.2012.049005

Segismundo, A., & Miguel, P. A. C. (2008). Failure mode and effects analysis (FMEA) in the context of risk management in new product development. *International Journal of Quality & Reliability Management*, *25*(9), 899–912. doi:10.1108/02656710810908061

Trajkovski, J., & Antovski, L. (2013). Risk Management Framework That Meets the Implementation Challenges in IT-Centric Micro and Small Companies. *International Journal of Human Capital and Information Technology Professionals*, *4*(2), 16–26. doi:10.4018/jhcitp.2013040102

Wang, H., Zhou, J., Tang, Y., Liu, Z., Kang, A., & Chen, B. (2021). Flood economic assessment of structural measure based on integrated flood risk management: A case study in Beijing. *Journal of Environmental Management, 280*, 111701. 10.1016/j.jenvman.2020.111701

Weber, P., Medina-Oliva, G., Simon, C., & Iung, B. (2012). Overview on Bayesian networks applications for dependability, risk analysis and maintenance areas. *Engineering Applications of Artificial Intelligence, 25*(4), 671-682. 10.1016/j.engappai.2010.06.002

Mohamed Amine Messaoudi graduated in the Department of Computer Science in the Faculty of Sciences at the University of Sciences and Technology of Oran, Algeria. where he received his Magister degree in Computer Science in 2010. Currently, he is a PhD student at the same University. His research interests include the system dependability domain, risk management, graph theory, computer networks, and wireless sensor networks.

Latifa Dekhici is currently working as an associate professor in the faculty of mathematics of computer science at the University of Sciences and the technology of Oran (USTO- MB) and also a member of the LABGEM laboratory in the High School of electrical and electronic engineering of Oran. She has received her engineering diploma in computer Sciences in 2002, then her magister degree in artificial intelligence and pattern recognition in 2005 and she obtained a PhD degree from the same university. Her thesis was about operating theatres modelling and surgeries scheduling. Dr Dekhici contributed to many combinatorial optimization fields as power dispatch, power system design, healthcare scheduling and green vehicles routing. She presented new versions of bio-inspired metaheuristics in several international journal papers and in 3 books.

Myriam Noureddine is associate Professor in the Department of Computer Science in the University of Sciences and Technology of Oran (USTO). Among her research interests, the dependability domain is important dealing with the failure diagnosis, the risk management and the system reliability, with application in industrial systems and computer networks.