

<sub>1</sub> A Unified Modeling Framework to Abstract  
<sub>2</sub> Knowledge of Dynamically Adaptive Systems

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# Abstract

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**Vision:** As state-of-the-art techniques fail to model efficiently the evolution and the uncertainty existing in dynamically adaptive systems, the adaptation process makes suboptimal decisions. To tackle this challenge, modern modeling frameworks should efficiently encapsulate time and uncertainty as first-class concepts.

*Context* Smart grid approach introduces information and communication technologies into traditional power grid to cope with new challenges of electricity distribution. Among them, one challenge is the resiliency of the grid: how to automatically recover from any incident such as overload? These systems therefore need a deep understanding of the ongoing situation which enables reasoning tasks for healing operations. **Abstraction** is a key technique that provided an illuminating description of systems, their behaviors, and/or their environments alleviating their complexity. **Adaptation** is a cornerstone feature that enables reconfiguration at runtime for optimizing software to the current and/or future situation.

Abstraction technique is pushed to its paramountcy by the model-driven engineering (MDE) methodology. However, information concerning the grid, such as loads, is not always known with absolute confidence. Through the thesis, this lack of confidence about data is referred to as **data uncertainty**. They are approximated from the measured consumption and the grid topology. This topology is inferred from fuse states, which are set by technicians after their services on the grid. As humans are not error-free, the topology is therefore not known with absolute confidence. This data uncertainty is propagated to the load through the computation made. If it is neither present in the model nor not considered by the adaptation process, then the adaptation

1 process may make suboptimal reconfiguration decision.

2 The literature refers to systems which provide adaptation capabilities as dynamically  
3 adaptive systems (DAS). One challenge in the grid is the phase difference between the  
4 monitoring frequency and the time for actions to have measurable effects. Action with  
5 no immediate measurable effects are named **delayed action**. On the one hand, an  
6 incident should be detected in the next minutes. On the other hand, a reconfiguration  
7 action can take up to several hours. For example, when a tree falls on a cable and cuts  
8 it during a storm, the grid manager should be noticed in real time. The reconfiguration  
9 of the grid, to reconnect as many people as possible before replacing the cable, is done  
10 by technicians who need to use their cars to go on the reconfiguration places. In a fully  
11 autonomous adaptive system, the reasoning process should be considered the ongoing  
12 actions to avoid repeating decisions.

13 *Problematic* **Data uncertainty and delayed actions are not specific to smart**  
14 **grids.**

15 First, data are, almost by definition, uncertain and developers always work with  
16 estimates. Hardware sensors have by construction a precision that can vary accord-  
17 ing to the current environment in which they are deployed. A simple example is the  
18 temperature sensor that provides a temperature with precision to the nearest degree.  
19 Software sensors approximate also values from these physical sensors, which increases  
20 the uncertainty. For example, CPU usage is computed counting the cycle used by a  
21 program. As stated by Intel, this counter is not error-prone<sup>1</sup>.

22 Second, it always exists a delay between the moment where a suboptimal state is  
23 detected by the adaptation process and the moment where the effects of decisions taken  
24 are measured. This delayed is due to the time needed by a computer to process data  
25 and, eventually, to send orders or data through networks. For example, migrating a  
26 virtual machine from a server to another one can take several minutes.

27 **Through this thesis, I argue that this data uncertainty and this delay**  
28 **cannot be ignored for all dynamic adaptive systems.** To know if the data un-  
29 certainty should be considered, stakeholders should wonder **if this data uncertainty**

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<sup>1</sup><https://software.intel.com/en-us/itc-user-and-reference-guide-cpu-cycle-counter>

1 **affects the result of their reasoning process, like adaptation.** Regarding delayed  
2 action, they should verify **if the frequency of the monitoring stage is lower than**  
3 **the time of action effects to be measurable.** These characteristics are common  
4 to smart grids, cloud infrastructure or cyber-physical systems in general.

5 *Challenge* These problematics come with different challenges concerning the represen-  
6 tation of the knowledge for DAS. The global challenge address by this thesis is: **how**  
7 **to represent the uncertain knowledge allowing to efficiently query it and to**  
8 **represent ongoing actions in order to improve adaptation processes?**

9 *Vision* **This thesis defends the need for a unified modeling framework which**  
10 **includes, despite all traditional elements, temporal and uncertainty as first-**  
11 **class concepts.** Therefore, a developer will be able to abstract information related to  
12 the adaptation process, the environment as well as the system itself.

13 Concerning the adaptation process, the framework should enable abstraction of the  
14 actions, their context, their impact, and the specification of this process (requirements  
15 and constraints). It should also enable the abstraction of the system environment and its  
16 behavior. Finally, the framework should represent the structure, behavior and specifi-  
17 cation of the system itself as well as the actuators and sensors. All these representations  
18 should integrate the data uncertainty existing.

19 *Contributions* Towards this vision, this document presents two approaches: a temporal  
20 context model and a language for uncertain data.

21 The temporal context model allows abstracting past, ongoing and future actions  
22 with their impacts and context. First, a developer can use this model to know what the  
23 ongoing actions, with their expect future impacts on the system, are. Second, she/he  
24 can navigate through past decisions to understand why they have been made when they  
25 have led to a sub-optimal state.

26 The language, named Ain'tea, integrates data uncertainty as a first-class concept. It  
27 allows developers to attach data with a probability distribution which represents their  
28 uncertainty. Plus, it mapped all arithmetic and boolean operators to uncertainty prop-  
29 agation operations. And so, developers will automatically propagate the uncertainty

1 of data without additional effort, compared to an algorithm which manipulates certain  
2 data.

3 *Validation* Each contribution has been evaluated separately. The language has been  
4 evaluated through two axes: its ability to detect errors at development time and its  
5 expressiveness. Ain'tea can detect errors in the combination of uncertain data earlier  
6 than state-of-the-art approaches. The language is also as expressive as current ap-  
7 proaches found in the literature. Moreover, we use this language to implement the load  
8 approximation of a smart grid furnished by an industrial partner, Creos S.A.<sup>2</sup>.

9 The context model has been evaluated through the performance axis. The disser-  
10 tation shows that it can be used to represent the Luxembourg smart grid. The model  
11 also provides an API which enables the execution of query for diagnosis purpose. In  
12 order to show the feasibility of the solution, it has also been applied to the use case  
13 provided by the industrial partner.

14 **Keywords:** dynamically adaptive systems, knowledge representation, model-driven  
15 engineering, uncertainty modeling, time modeling

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<sup>2</sup>Creos S.A. is the power grid manager of Luxembourg. <https://www.creos-net.lu>

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<sup>1</sup> **Abbreviations**

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<sup>2</sup> **Glossary**

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## 2 Introduction

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11     **Abstract:** *Model-driven engineering methodology and dynamically adaptive systems*  
12 *approach are combined to tackle new challenges brought by systems nowadays. After*  
13 *introducing these two software engineering techniques, I give one example of such sys-*  
14 *tems: the Luxembourg smart grid. I will also use this example to highlight two of the*  
15 *problematics: uncertainty of data and delays in actions. Among the different challenges*  
16 *which are implied by them, I present the global one addressed by the vision defended in*  
17 *this thesis: modeling of temporal and uncertain data. This global challenge can be ad-*  
18 *dressed by splitting up in several ones. I present two of them, which are directly tackled*  
19 *by two contributions presented in this thesis.*

## **1 Introduction**

## **2 Use case: Luxembourg smart grid**

3      Should contain: - veg iqu grqaub

## **4 General background**

5      should contain: - MDE / metamodel / model - DAS

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## TKM: a temporal knowledge model to represent actions, their contexts and their impacts

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**Abstract:** *Adaptation processes are executed with a high frequency to react to any incidents whereas the execution of their decisions is constrained by the executions of delayed actions. We identified two problems that result from these different paces. First, unfinished actions, together with their expected effects, over time are not considered, leading upcoming analysis phases potentially make suboptimal decisions. Second, explanation of the adaptation process remains challenging due to the lack of tracing ability of current approaches. To tackle this problem, we first propose a knowledge formalism to define the concept of a decision. Second, we describe a novel temporal knowledge model to represent, store and query decisions as well as their relationship with the knowledge*

1 *(context, requirements, and actions). We validate our approach through a use case based*  
2 *on the smart grid at Luxembourg. We also demonstrate its scalability both in terms of*  
3 *execution time and consumed memory.*

# 1 Introduction

2 Adaptive systems have proven their suitability to handle the increasing complex-  
3 ity of system and their ever-changing environment. To do so, they make adaptation  
4 decisions, in the form of actions, based on high-level policies. For instance, the Open-  
5 Stack Watcher project [**OpenStack:Watcher:Wiki**] implements a MAPE-k loop to  
6 assist cloud administrators in their activities to tune and rebalance their cloud resources  
7 according to some optimization goals (e.g., CPU and network bandwidth). For read-  
8 ability purpose, we refer to adaptation decision as decision in the remaining part of this  
9 document.

10 Despite the reactivity of adaptation processes, impacts of their decisions can be  
11 measurable long after they have been taken. We identified two problematics caused by  
12 this difference of paces:

- 13 • How to reason over unfinished actions and their expected effects?
- 14 • How to diagnose the self-adaptation process?

15 To address them, we propose a temporal knowledge model which can trace its deci-  
16 sions over time, along with their circumstances and effects. By storing them, the adap-  
17 tation process could consider the ongoing actions with their expected effects. Plus, in  
18 case of faulty decisions, developers may trace back their effects to their circumstances.

19 The rest of this chapter is structured as follows. In the remaining part of this section,  
20 we motivate our approach, we summarize core concepts manipulated in adaptation  
21 processes, and we present a use case scenario based on the Luxembourg Smart Grid  
22 (*cf.* Chapter **TODO: add ref**). Then, we provide a formal definition of these  
23 concepts in Section 2.2. Later, we describe the proposed data model in Section 2.3.  
24 In Section 2.4, we demonstrate the applicability of our approach by applying it to the  
25 smart grid example. We conclude this chapter in Section 2.5.

## 26 Motivation

### 27 Delayed action

28 In this section we will motivate the need to reason over delayed actions. To do so, we  
29 will first give four examples of these actions in. Then we detail why the effects of actions

1 should be considered. Finally, we summarize and motivate the need for incorporating  
2 actions and their effect in the knowledge.

3 **Delayed action examples** Until here, we claim that adaptation process should han-  
4 dle delayed actions. In order to show their existence, we will give four different examples:  
5 two from our use case, one from cloud infrastructures and one from smart homes. From  
6 our understanding, three phenomena can explain this delay: the time to execute the  
7 action (*cf.* Example 1), the time for the system to handle the new configuration (*cf.*  
8 Example 3) and the inertia of the measured element (*cf.* Example 2 and 4).

9 **Example 1: Modification of fuse states in smart grids** Even if the Luxem-  
10 bourg power grid is moving to an autonomous one, not all the elements can be remotely  
11 controlled. One example is the fuses, they still need to be open or close by a human.  
12 In this document, open and close actions in the smart grid imply technicians who are  
13 contacted, drive to fuses places and manually change fuse states. If several fuses need  
14 to be changed, one technician may have to drive to them, sequentially, and executes  
15 the modifications. For example, in our case our industrial partner asks us to consider  
16 that each fuse modification should take in average 15 min whereas any incident should  
17 be detected in the minute. Let's imagine that an incident is detected at 4p.m. and  
18 can be solved by modifying three fuses. Before the incident will be marked as resolved,  
19  $15min * 3 = 45min$ . The incidents will be seen as resolved by the adaptation process  
20 at 4:45p.m. In summary, the delay of the action is due to the execution time that is  
21 not immediate.

22 **Example 2: Reduction of amps limit in smart grids<sup>1</sup>** In his smart grid  
23 project, Creos envisages controlling remotely amps limits of the grid users. Specific  
24 plugs will be furnished to them, which will allow them managing what can be controlled  
25 and what cannot be. One example of those is plugs to load electric vehicles. However,  
26 due to how power consumption is measured by meters, and even if the action is near  
27 instant, the impacts of the action would not be visible immediately. Indeed, data  
28 received by Creos corresponds to the total energy consumed since the installation.

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<sup>1</sup>This example is based on randomly generated data. As this action is not yet available on the Luxembourg smart grid, we miss real data. However, it reflects an hypothesis shared with our partner.

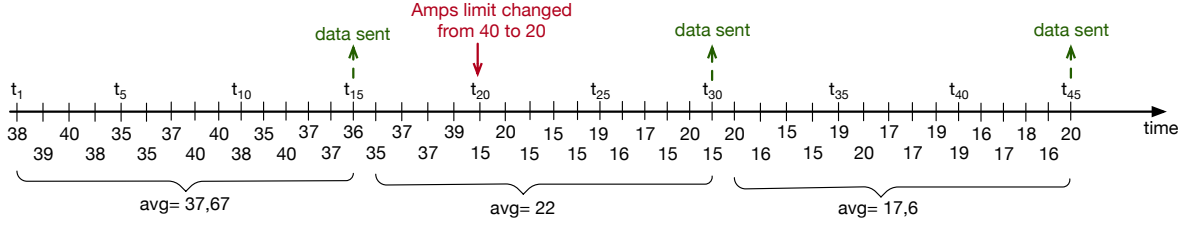


Figure 2.1: Example of consumption measurement before and after a limitation of amps has been executed at  $t_{20}$ .

1 From this information, only the average of consumed data for the last period can be  
2 computed.

3 In Figure 2.1, we depict a scenario that shows the delay between the action is  
4 executed and the impacts are measured. Each timepoint represents one minute, with  
5 the consumption at this moment.

6 Let's imagine a customer who has his or her limit set to 40 amps<sup>2</sup> and consume near  
7 this limit. We consider that data are sent every 15 min. After receiving data sent at  $t_{15}$   
8 and processing them, the adaptation process detects an overload and decides to reduce  
9 the limits to 20 amps for the customer. However, considering the delay for data to be  
10 collected and the one to sent data<sup>3</sup>, the order is received and executed at  $t_{20}$ . At  $t_{30}$ ,  
11 new data consumption are sent, here equal to 22 amps. Here there is two situations.  
12 First, this reduction was enough to fix the overload. Even in this idealistic scenario, the  
13 adaptation process should wait at worst 15min ( $t_{30} - t_{15}$ ) to see the resolution (without  
14 considering the communication time). Second, this reduction was not enough - as the  
15 adaptation process considered that the consumption data will be at worst 20 amps and  
16 here it is 22. Before seeing the incident as solved, the adaptation process should wait  
17 new data, sent at  $t_{45}$ . It should wait around 30min ( $t_{45} - t_{15}$ ) for this.

18 In summary, the delay of this action can be explained by the inertia in the con-  
19 sumption measurement.

20 **Example 3: Switching off a machine from a load balancer** An example in  
21 cloud infrastructure of long actions is to remove a machine from a load balancer, for

<sup>2</sup>It means that the user cannot consume more than 40 amps at a precise time  $t_i$ .

<sup>3</sup>Reminder: the smart grid is not built upon a fast network such a fiber network.

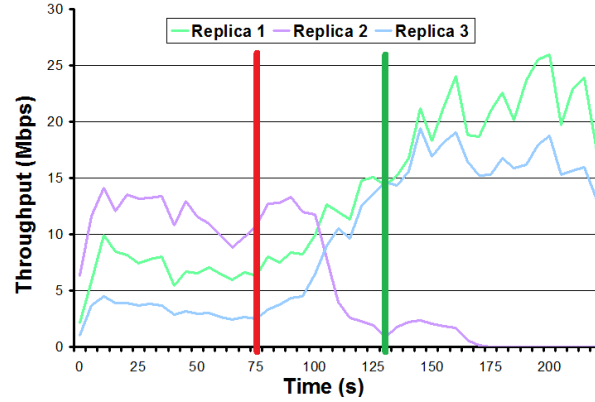


Figure 2.2: Figure extracted from [DBLP:conf/nsdi/WangBR11] that shows the delay between the time where the machine Replica 2 (R2) stop receiving new connections to prepare its disconnection (depicted by the red bar), effective around 100s later. The green bar represents the moment where the all the rules in the load balancer stop considering R2.

example during a scale down operation. Scale down operation allows cloud manager to reduce allocated resources for a specific case. It is used either to reduce the cost of the infrastructure or to reallocate them to other tasks. In [DBLP:conf/nsdi/WangBR11], Wang *et al.*, present a load-balancing algorithm. In their evaluation, they present the figure depicted in Figure 2.2 that show the evolution of the throughput after the server Replica 2 (R2) is removing from the load balancer. The red bars shows the moment where stop receiving new connection and the green one shows the moment where it is removed from the load balancer algorithm. However, despite these actions have been taken, R2 should finish the ongoing tasks that it is executing. This explain why the throughput is progressively decreasing to 0 and there is a delay of around 100s between the red bars and the moment where is a no connection.

This example shows a delayed action due to the time required by the system to handle the new configuration.

**Example 4: Modifying home temperature through a smart home system**  
Smart home systems have been implemented in order to remotely manage a house or to automatically perform routines. For example, it allows users to close or open blinds



1 from their smartphones from anyplace, even outside the house. The temperature can  
2 be automatically manage by such systems, for example given targeted temperature at  
3 precise time. However, heating or cooling a house is not immediate, it can take several  
4 hours before the targeted temperature is reached. Plus, if the temperature sensor and  
5 the heating or cooling system or not placed nearby, the new temperature can take time  
6 before being measured. This can be explained due to the temperature inertia plus the  
7 delay for the temperature to be propagated.

8 Through these four examples, we show that delayed actions can be found in different  
9 kind of systems, from CPS to cloud infrastructure. However, not only knowing that  
10 an action is running is important but also knowing its expecting effect. We detail this  
11 point in the next section.

12 **The need to consider effects** In the previous section we show the existence of de-  
13 layed actions. One may argue that action status is already integrated in the knowledge.  
14 For example, the OpenStack Watcher framework stores them in a data base <sup>4</sup>, acces-  
15 sible through an API. However, for the best of our knowledge Watcher does not store  
16 the expecting effects of each action. While the adaptation process knows what action  
17 is running, it does not know what it should expect from them.

18 Considering our example based on the modification of fuses, if the system knows  
19 that the technician is modifying fuse states, it may not know what would be the effects.  
20 In this case, when the adaptation process analyses the system context it may wonder:  
21 what will be the next grid configuration? how the load will be balanced? will the  
22 future configuration fix all the current incidents? If the effects are not considered by  
23 the adaptation process, then it may take suboptimal decisions.

24 Let's exemplify this claim through a scenario based on the modification of fuses  
25 example. At  $t_0$  an overload in one cable is detected and the state of three fuses need  
26 to be modified. As explained in the previous section, this will take around 45 min. We  
27 consider that the system can mark a incident as "being resolved". In the knowledge, two  
28 informations are therefore stored: the fact the the overload incident is being resolved  
29 and the fact it is done by modifying three fuses. However, during the resolution stage,

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<sup>4</sup><https://docs.openstack.org/watcher/latest/glossary.html#watcher-database-definition>

1 another cable is overloading. With these informations, the system can either wait the  
2 end of the resolution of the first incident to see if both overloads will be fix or it take  
3 other actions without considering the ongoing actions. Applying the first strategy may  
4 make the resolution of the second incident late, whereas the second one may generate  
5 suboptimal sequence of actions. For example, the second modifications may undo what  
6 have been done before or both actions may be conflicting.

7 **Conclusion** Actions, like fuse modification in a smart grid or removing a server  
8 from a load balancer, generated during by adaptation proecess could take time upon  
9 completion. Moreover, the expected effects resulting from such action is reflected in the  
10 context representation only after a certain delay. One used workaround is the selection,  
11 often empirically, of an optimistic time interval between two iterations of the MAPE-K  
12 loop such that this interval is bigger than the longest action execution time. However,  
13 the time to execute an action is highly influenced by system overload or failures, making  
14 such empirical tuning barely reliable. We argue that by enriching context representation  
15 with support for past and future planned actions and their expected effects over time,  
16 we can highly enhance reasoning processes and avoid empirical tuning.

17 Fined and rich context information directly influences the accuracy of the actions  
18 taken. Various techniques to represent context information have been proposed; among  
19 which we find the models@run.time [DBLP:journals/computer/MorinBJFS09;  
20 DBLP:journals/computer/BlairBF09]. The models@run.time paradigm inherits  
21 model-driven engineering concepts to extend the use of models not only at design time  
22 but also at runtime. This model-based representation has proven its ability to structure  
23 complex systems and synthesize its internal state as well as its surrounding environment.

24 In this thesis, we propose therefore a meta-model of the knowledge which include  
25 action and their effects. Our current approach is limited to the representation of mea-  
26 surable effects of any action.

## 27 **Diagnosis support**

28 Faced with growingly complex and large-scale software systems (e.g. smart grid  
29 systems), we can all agree that the presence of residual defects becomes unavoid-  
30 able [DBLP:conf/icse/BarbosaLMJ17; DBLP:conf/icse/MongielloPS15; DBLP:conf/icse/H.

1 Even with a meticulous verification or validation process, it is very likely to run into  
 2 an unexpected behavior that was not foreseen at design time. Alone, existing formal  
 3 modeling and verification approaches may not be sufficient to anticipate these fail-  
 4 ures [DBLP:conf/icse/TaharaOH17]. As such, complementary techniques need to  
 5 be proposed to locate the anomalous behavior and its origin in order to handle it in a  
 6 safe way.

7 As there might be many probable causes behind an abnormal behavior, developers  
 8 usually perform a set of diagnosis routines to narrow down the scope or origin of the fail-  
 9 ure. One way to do so is by investigating the satisfaction of its requirements and the de-  
 10 cisions that led to this system state, as well as their timing [DBLP:conf/iceccs/BencomoWSW12].  
 11 In this perspective, developers may set up a set of systematic questions that would help  
 12 them understand why and how the system is behaving in such a way. These questions  
 13 may comprise:

- 14 • what goal(s) the system was trying to reach by executing a tactic  $a$ ?
- 15 • what were the circumstances used by a decision  $d$  and its expected impact on the
- 16 context?
- 17 • what decision(s) influenced the system's context at a time  $t$ ?

18 Bencomo *et al.*, [DBLP:conf/iceccs/BencomoWSW12] argue that comprehen-  
 19 sive explanation about the system behavior contributes drastically to the quality of the  
 20 diagnosis, and eases the task of troubleshooting the system behavior. To enable this,  
 21 we believe that adaptive software systems should be equipped with traceability man-  
 22 agement facilities to link the decisions made to their **(i) circumstances, that is to**  
 23 **say, the history of the system states and the targeted requirements, and (ii)**  
 24 **the performed actions with their impact(s) on the system.** In particular, an  
 25 **adaptive system should keep a trace of the relevant historical events.** Ad-  
 26 ditionally, it should be able to **trace the goals intended to be achieved by the**  
 27 **system to the adaptations and the decisions that have been made, and vice**  
 28 **versa.** Finally, in order to enable developers to interact with the system in a clear and  
 29 understandable way, appropriate abstraction to **enable the navigation of the traces**  
 30 **and their history should also be provided.** Unfortunately, suitable solutions to  
 31 support these features are under-investigated.

Existing approaches [hassel13; heinrich14; ehlers11; DBLP:conf/icse/MendoncaAR14; DBLP:conf/icse/CasanovaGSA14; DBLP:conf/icse/IftikharW14a] are accompanied by built-in monitoring rules and do not allow to interact with the underlying system in a simple way. Moreover, they do not keep track of historical changes as well as causal relationships linking requirements to their corresponding adaptations. Only flat execution logs are stored.

In this document, we propose a framework to structure and store the state and behavior of a running adaptive system, together with a high-level API to efficiently perform diagnosis routines. Our framework relies on a temporal model-based solution that efficiently abstracts decisions and their corresponding circumstances. Specifically, based on existing approaches for modeling and monitoring adaptation processes, we identify a set of properties that characterize context, requirements, and actions in self-adaptive systems. Then, we formalize the common core concepts implied in adaptation processes, also referred to as knowledge, by means of temporal graphs and a set of relations that trace decisions impact to circumstances. Finally, thanks to exposing common interfaces in adaptive processes, existing approaches in requirements and goal modeling engineering can be easily integrated into our framework.

## Background

Before formalizing and modeling decisions and their circumstances, we abstract common concepts implied in an adaptation process. We refer to these concepts as the knowledge.

### General concepts of adaptation process

Similar to the definition provided by Kephart [DBLP:journals/computer/KephartC03], IBM defines adaptive systems as “a computing environment with the ability to manage itself and **dynamically adapt** to change in accordance with **business policies and objectives**. [These systems] can perform such activities based on **situations they observe or sense in the IT environment** [...]” [computing2006architectural].

Based on this definition, we can identify three principal concepts involved in adaptation processes. The first concept is *actions*. They are executed in order to perform

1 a dynamic adaptation through actuators. The second concept is **business policies**  
2 **and objectives**, which is also referred to as the **system requirements** in the domain  
3 of (self-)adaptive systems. The last concept is the observed or sensed **situation**, also  
4 known as the **context**. The following subsections provide more details about these  
5 concepts.

## 6 Context

7 In this thesis, we use the widely accepted definition of context provided by Dey [DBLP:journals/puc  
8 “Context is **any information that can be used to characterize** the situation  
9 of an entity. An entity is a person, place, or object that is considered relevant to  
10 the interaction between a user and [the system], including the user and [the sys-  
11 tem] themselves”. In this section, we list the characteristics of this information based  
12 on several works found in the literature [DBLP:conf/pervasive/HenricksenIR02;  
13 chong2007context; DBLP:conf/seke/0001FNMKT14; bettini2010survey; DBLP:journals/co  
14 We use them to drive our design choices of our Knowledge meta-model (cf. Sec-  
15 tion *TODO: Add ref* ).

16 **Volatility** Data can be either **static** or **dynamic**. Static data, also called frozen, are  
17 data that will not be modified, over time, after their creation [DBLP:conf/pervasive/HenricksenIR0  
18 DBLP:journals/comsur/MakrisSS13; bettini2010survey; chong2007context].  
19 For example, the location of a machine, the first name or birth date of a user can be  
20 identified as static data. Dynamic data, also referred to as volatile data, are data that  
21 will be modified over time.

22 **Temporality** In dynamic data, sometimes we may be interested not only in stor-  
23 ing the latest value, but also the previous ones [DBLP:conf/seke/0001FNMKT14;  
24 DBLP:conf/pervasive/HenricksenIR02; chong2007context]. We refer to these  
25 data as **historical** data. Temporal data is not only about past values, but also future  
26 ones. Two kinds of future values can be identified, **predicted** and **planned**. Thanks  
27 to machine learning or statistical methods, dynamic data values can be **predicted**.  
28 **Planned** data are set by a system or a human to specify planned modification on the  
29 data.

**Uncertainty** One of the recurrent problems facing context-aware applications is the data uncertainty [DBLP:conf/dagstuhl/LemosGMSALSTVVWBBBBBCDDEGGGGIKKLMM; DBLP:conf/pervasive/HenricksenIR02; DBLP:journals/comsur/MakrisSS13; bettini2010survey]. Uncertain data are not likely to represent the reality. They contain a noise that makes it deviate from its original value. This noise is mainly due to the inaccuracy and imprecision of sensors. Another source of uncertainty is the behavior of the environment, which can be unpredictable. All the computations that use uncertain data are also uncertain by propagation.

**Source** According to the literature, data sources are grouped into two main categories, either sensed (measured) data or computed (derived) data [DBLP:journals/comsur/PereraZCchong2007context].

**Connection** Context data entities are usually linked using three kinds of connections: conceptual, computational, and consistency [DBLP:conf/pervasive/HenricksenIR02; bettini2010survey]. The conceptual connection relates to (direct) relationships between entities in the real world (e.g. smart meter and concentrator). The computational connection is set up when the state of an entity can be linked to another one by a computation process (derived, predicted). Finally, the consistency connection relates entities that should have consistent values. For instance, temperature sensors belonging to the same geographical area.

## Requirement

Adaptation processes aim at modifying the system state to reach an optimal one. All along this process, the system should respect the **system requirements** established ahead. Through this paper, we use the definition provided by IEEE [iso2017systems]: “(1) Statement that translates or expresses a need and its associated **constraints** and **conditions**, (2) **Condition or capability that must be met or possessed** by a system [...] to satisfy an agreement, standard, specification, or other formally imposed documents”.

Although in the literature, requirements are categorized as functional or non-functional, in this paper we use a more elaborate taxonomy introduced by Glinz [DBLP:conf/re/Glinz07]. It classifies requirements in four categories: functional, performance, specific quality,

1 and constraint. All these categories share a common feature: they are all temporal.  
2 During the life-cycle of an adaptive system, the developer can update, add or remove  
3 some requirements [DBLP:conf/icse/ChengA07; pandey2010effective].

#### 4 **Action**

5 In the IEEE Standards [iso2017systems], an action is defined as: “**process of**  
6 **transformation** that **operates upon data** or other types of inputs to create data,  
7 produce outputs, or **change the state** or condition of the subject software”.

8 Back to adaptive systems, we can define an action as a process that, given the  
9 context and requirements as input, adjusts the system behavior. This modification will  
10 then create new data that correspond to an output context. In the remainder of this  
11 paper, we refer to output context as impacted context, or simply impact(s). Whereas  
12 requirements are used to add preconditions to the actions, context information is used  
13 to drive the modifications. Actions execution have a start time and a finish time. They  
14 can either succeed, fail, or be canceled by an internal or external actor.

#### 15 **Use case scenario**

### 16 **Knowledge formalization**

17 As discussed previously, I consider **knowledge** to be the association of **context** in-  
18 formation, **requirements**, and **action** information, all in one global and unified model.  
19 While **context** information captures the state of the system environment and its sur-  
20 roundings, the system **requirements** define the constraints that the system should satisfy  
21 along the way. The **actions**, on the other hand, are means to reach the goals of the  
22 system.

23 In this section, I provide a formalization of the **knowledge** used by adaptation pro-  
24 cesses based on a temporal graph. Indeed, due to the complexity and interconnectivity  
25 of system entities, graph data representation seems to be an appropriate way to repre-  
26 sent the **knowledge**. Augmented with a temporal dimension, temporal graphs are then  
27 able to symbolize the evolution of system entities and states over time. We benefit  
28 from the well-defined graph manipulation operations, namely temporal graph pattern  
29 matching and temporal graph relations to represent the traceability links between the

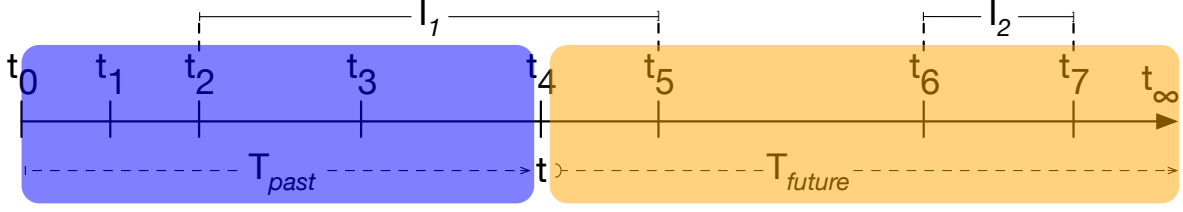


Figure 2.3: Time definition used for the knowledge formalism

1 **decisions** made and their **circumstances**.

2 Before describing this formalism, I describe the semantic used for the temporal axis.  
 3 Then, I exemplify the knowledge formalism using the Luxembourg smart grid use case.

#### 4 **Formalization of the temporal axis**

5 The formalism describe below has been made with two goals in mind. First, the  
 6 definition of the time space should allow the distinction between past and future. Doing  
 7 this distinction enable the differentiation between measured data and estimated (or  
 8 predicted data). Second, it should permit the definition of the life cycle of an element  
 9 of the **knowledge**, which can be seen as a succession of states with a validity period that  
 10 should not overlap each other.

11 Time space  $T$  is considered as an ordered discrete set of time points non-uniformly  
 12 distributed. As depicted in Figure 2.3, this set can be divided into 3 different subsets  
 13  $T = T_{past} \cup \{t\} \cup T_{future}$ , where:

- 14 •  $T_{past}$  is the sub-domain  $\{t_0; t_1; \dots; t_{current-1}\}$  representing graph data history start-  
 15 ing from  $t_0$ , the oldest point, until current time,  $t$ , excluded.
- 16 •  $\{t\}$  is a singleton representing the current time point
- 17 •  $T_{future}$  is sub-domain  $\{t_{current+1}; \dots; t_{\infty}\}$  representing future time points

18 The three domains depend completely on the current time  $\{t\}$  as these subsets slide  
 19 as time passes. At any point in time, these domains never overlap:  $T_{past} \cap \{t\} = \emptyset$ ,  
 20  $T_{future} \cap \{t\} = \emptyset$ , and  $T_{past} \cap T_{future} = \emptyset$ . The definition of these three subsets reaches  
 21 the first goal.

22 In addition, there is a right-opened time interval  $I \in T \times T$  as  $[t_s, t_e)$  where  $t_e - t_s > 0$ .  
 23 In English words, it means that the interval cannot represent a single time point and



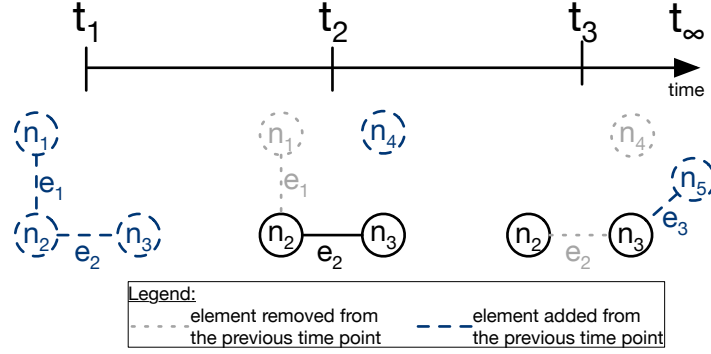


Figure 2.4: Evolution of a temporal graph over time

1 should follow the time order. For any  $i \in I$ ,  $start(i)$  denotes its lower bound and  
 2  $end(i)$  its upper bound. As detailed in Section ??, these intervals are used to define  
 3 the validity period for each node of the graph.

4 Figure 2.3 displays an example of a time space  $T_1 = \{t_0, t_1, t_2, t_3, t_4, t_5, t_6, t_7\}$ . Here,  
 5 the current time is  $t = t_4$ . According to the definition of the past subset ( $T_{past}$ ) and  
 6 the future one ( $T_{future}$ ), there is:  $T_{past1} = \{t_0, t_1, t_2, t_3\}$  and  $T_{future1} = \{t_5, t_6, t_7\}$ . Two  
 7 intervals have been defined on  $T_1$ , namely  $I_1$  and  $I_2$ . The first one starts at  $t_2$  and ends  
 8 at  $t_5$  and the last one is defined from  $t_6$  to  $t_7$ . As shown with  $I_1$ , an interval could be  
 9 defined on different subsets, here it is on all of them ( $T_{past}$ ,  $t$ , and  $T_{future}$ ).

## 10 Formalism

11 **Graph definition** First, let  $K$  be an adaptive process over a system **knowledge** rep-  
 12 resented by a graph such as  $K = (N, E)$ , comprising a set of nodes  $N$  and a set of edges  
 13  $E$ . Nodes represent any element of the knowledge (context, actions, *etc.*) and edges  
 14 represent their relationships. Nodes have a set of attribute values. An attribute value  
 15 has a type (numerical, boolean, ...). Every relationship  $e \in E$  can be considered as  
 16 a couple of nodes  $(n_s, n_t) \in N \times N$ , where  $n_s$  is the source node and  $n_t$  is the target  
 17 node.

18 **Adding the temporal dimension** In order to augment the graph with a temporal  
 19 dimension, the relation  $V^T$  is added. So now the knowledge  $K$  is defined as a temporal  
 20 graph such as  $K = (N, E, V^T)$ .

1 A node is considered valid either until it is removed or until one of its attributes  
2 value changes. In the latter case, a new node with the updated value is created. Whilst,  
3 an edge is considered valid until either its source node and target node is valid, or until  
4 the edge itself is removed. Otherwise, nodes and edges are considered invalid. The  
5 temporal validity relation is defined as  $V^T : N \cup E \rightarrow I$ . It takes as a parameter a node  
6 or an edge ( $k \in N \cup E$ ) and returns a time interval ( $i \in I$ , cf. Section 2.2.1) during  
7 which the graph element is valid.

8 Figure 2.4 shows an example of a temporal graph  $K_1$  with five nodes ( $n_1, n_2, n_3,$   
9  $n_4$ , and  $n_5$ ) and three edges ( $e_1, e_2$ , and  $e_3$ ) over a lifecycle from  $t_1$  to  $t_3$ . In this  
10 way,  $K_1$  equals to  $(\{n_1, n_2, n_3, n_4, n_5\}, \{e_1, e_2, e_3\}, V_1^T)$ . Let's assume that the graph is  
11 created at  $t_1$ . As  $n_1$  is modified at  $t_2$ , its validity period starts at  $t_1$  and ends at  $t_2$ :  
12  $V_1^T(n_1) = [t_1, t_2)$ .  $n_2$  and  $n_3$  are not modified; their validity period thus starts at  $t_1$   
13 and ends at  $t_\infty$ :  $V_1^T(n_2) = V_1^T(n_3) = [t_1, t_\infty)$ . Regarding the edges, the first one,  $e_1$ , is  
14 between  $n_1$  and  $n_2$  and the second one,  $e_2$  from  $n_2$  to  $n_3$ . Both are created at  $t_1$ . As  
15  $n_1$  is being modified at  $t_2$ , its validity period goes from  $t_1$  to  $t_2$ :  $V_1^T(e_1) = [t_1, t_2)$ .  $e_2$  is  
16 deleted at  $t_3$ . Its validity period is thus equal to:  $V_1^T(e_2) = [t_1, t_3)$ .

17 **Lifecycle of a knowledge element** One node represents the state of exactly one  
18 knowledge element during a period named the validity period. The lifecycle of a knowl-  
19 edge element is thus modeled by a unique set of nodes. By definition, the validity  
20 periods of the different nodes cannot overlap. A same time period cannot be repre-  
21 sented by two different nodes, which could create inconsistency in the temporal graph.

22 To keep track of this knowledge element history, the  $Z^T$  relation is added to the  
23 graph formalism:  $K = (N, E, V^T, Z^T)$ . It serves to trace the updates of a given knowl-  
24 edge element at any point in time. This relation can also be seen as a temporal identity  
25 function which takes as parameters a given node  $n \in N$  and a specific time point  $t \in T$ ,  
26 and returns the corresponding node at that point. Formally,  $Z^T : N \times T \rightarrow N$ .

27 In order to consider this new relation in the example presented in Figure 2.4, the  
28 definition of  $K_1$  is modified to  $K_1 = (\{n_1, n_2, n_3, n_4, n_5\}, \{e_1, e_2, e_3\}, V_1^T, Z_1^T)$ . In Fig-  
29 ure 2.4, let's imagine that  $n_1, n_4$ , and  $n_5$  represent the same knowledge element  $k_e$ .  
30 The lifecycle of  $k_e$  is thus:

- 1     •  $n_1$  for period  $[t_1, t_2)$ ,
- 2     •  $n_4$  for period  $[t_2, t_3)$ ,
- 3     •  $n_5$  for period  $[t_3, t_\infty)$ .

4     Let  $t'_1$  be a timepoint between  $t_1$  and  $t_2$ . When one wants to resolve the node  
5     representing the knowledge element at  $t'_1$ , she or he gets  $n_1$  node, no matter of the node  
6     input ( $n_1$ ,  $n_4$ , or  $n_5$ ):  $Z_1^T(n_4, t_1) = n_1$ . On the other hand, applying the same relation  
7     with another node ( $n_2$  or  $n_3$ ) returns another node. For example, if  $n_2$  and  $n_3$  do not  
8     belongs to the same knowledge element, then it will return the node given as input, for  
9     example  $Z_1^T(n_2, t_1) = n_2$ .

10   **Knowledge elements stored in nodes** Nodes are used to store the different knowl-  
11   edge elements: context, requirements and actions. The set of nodes  $N$  is thus split in  
12   three subset:  $N = C \cup R \cup A$  where  $C$  is the set of nodes which store context informa-  
13   tion,  $R$  a set of nodes for requirement information and  $A$  the set of nodes for actions  
14   information.

15   Actions define a process that indirectly impact the context: they will change the  
16   behavior of the system, which will be reflected on the context information. Require-  
17   ments are also processes that are continuously run over the system in order to check the  
18   specifications. Here, the purpose of the  $A$  and  $R$  subset is not to store these processes  
19   but to list them. It can be thought as a catalogue of actions and requirements, with  
20   their history.

21   Using a high level overview, these processes can be depicted as: taking the knowl-  
22   edge as input, perform task, and modify this knowledge as output. As detailed in the  
23   next two paragraphs, they can be formalized by relations.

24   **Temporal queries for requirements** At the current state, the formalism of the  
25   knowledge  $K$  do not contain any information regarding the requirement processes. To  
26   overcome this, system requirements processes  $R_P$  are added such as  $K = (N, E, V^T, Z^T,$   
27    $R_P)$ .  $R_P$  is a set of patterns  $P_{[t_j, t_k]}(K)$  and queries  $Q$  over these patterns:  $R_P = P \cup Q$ .

28    $P_{[t_j, t_k]}$  denotes a temporal graph pattern, where  $t_j$  and  $t_k$  are the lower and upper  
29   bound of the time interval respectively. The time interval can be either fixed (absolute)  
30   or sliding (relative). Each element of the pattern should be valid for at least one time

1 point:  $\forall p \in P_{[t_j, t_k]}, V^T(e) \cap [t_j, t_k] \neq \emptyset$ . Patterns can be seen as temporal subgraph  
 2 of  $K$ , with a time limiting constraint coming in the form of a time interval. Temporal  
 3 graph queries  $Q$  consist commonly of two parts: (i) path description to traverse the  
 4 graph nodes, at both structural and temporal dimensions; (ii) arithmetic expressions  
 5 on nodes, edges, and attribute values.

6 **Temporal relations for actions** Like for  $R_P$ , the knowledge  $K$  needs to be aug-  
 7 mented with the action processes  $A_P$ :  $K = (N, E, V^T, Z^T, R_P, A_P)$ . Actions processes  
 8  $A_P$  can be regarded as a set of relations or isomorphisms mapping a source temporal  
 9 graph pattern  $P_{[t_j, t_k]}$  to a target one  $P_{[t_l, t_m]}$ ,  $A_P : K \times I \rightarrow K \times I$ .

10 The left-hand side of the relation depicts the temporal graph elements over which  
 11 an action is applied. Every relation may have a set of application conditions. They  
 12 describe the circumstances under which an action should take place. These application  
 13 conditions are either positive, should hold, or negative, should not hold. Application  
 14 conditions come in the form of temporal graph invariants. The side effects of these  
 15 actions are represented by the right-hand side.

16 Finally, we associate to  $A_P$  a temporal function  $E_{A_P}$  to determine the time interval  
 17 at which an action has been executed. Formally,  $X : A \rightarrow I$ .

18 **Temporal relations for decisions** Finally, the knowledge formalism needs to in-  
 19 clude the last, but not the least, element: decisions made by the adaptation,  $K = (N,$   
 20  $E, V^T, Z^T, R_P, A_P, D)$  While the source of relations in  $D$  represents the state before  
 21 the execution of an action, the target shows its impact on the **context**. Its intent is  
 22 **to trace back impacts of actions execution to the decisions they originated**  
 23 **from**.

24 A decision present in  $D$  is defined as a set of executed actions, *i.e.*, a subset of  $A_P$ .  
 25 Formally,  $D = \{ A_D \cup R_D \mid A_D \subseteq A_P, R_D \subseteq R_P \}$ . We assume that each action should  
 26 result from one decision:  $\forall a \in A, \forall d1, d2 \in D \mid a \in d1 \wedge a \in d2 \rightarrow d1 = d2$ .

27 The temporal function  $E_{A_P}$  is extended to decision in order to represent the execu-  
 28 tion time:  $E_{A_P} : (A \cup D) \rightarrow I$ . For decision, the lower bound of the interval correspond  
 29 to the lowest bound of the action execution intervals. Following the same principle, the  
 30 upper bound of the interval correspond to the uppermost bound of the action execu-

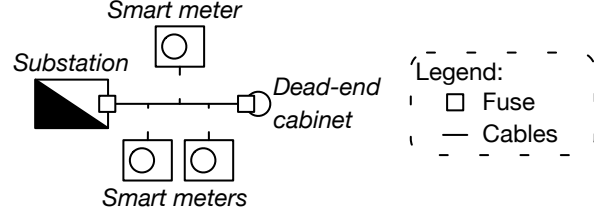


Figure 2.5: Simplified version of a smart grid

Figure 2.6: Representation of the smart grid context depicted in Figure 2.5

tion intervals. Formally,  $\forall d \in D \rightarrow E_{A_P}(d) = [l, u)$ , where  $l = \min_{a \in A_d} \{E_{A_P}(a)[start]\}$  and  $u = \max_{a \in A_d} \{E_{A_P}(a)[end]\}$ .

**Sum up** Knowledge of an adaptive system can be formalism with a temporal graph such as  $K = (N, E, V^T, Z^T, R_P, A_P, D)$ , wherein:

- $N$  is a set of nodes to represent the different information (context, actions and requirements)
- $E$  is a set of edges with connect the different nodes,
- $V^T$  is a temporal relation which defines the temporal validity of each elements,
- $Z^T$  is a relation to track the history of each knowledge elements,
- $R_P$  is a relation that define the different requirements processes,
- $A_P$  is a relation that define the different action processes,
- $D$  is a set of action processes that result from a same decision.

In the next section, we exemplify this formalism over our case study.

## Application on the use case

The example presented in Section 1.2 contain too much detail to provide a readable and understandable example of the formalism. Below, an excerpt of it is thus presented in order to overcome this problem.

**Excerpt of a smart grid** Figure 2.5 shows a simplified version of a smart grid with one substation, one cable, three smart meters and one dead-end cabinet. Both the substation and the cabinet have a fuse. The meters regularly send consumption data

at the same time. One requirement is considered for this example: minimizing the number of overloads. To achieve so, among the different actions, two actions are taken into account in this example: decreasing or increasing the amps limits of smart meters.

Let  $K_{SG}$  be the temporal graph that represents the knowledge of this adaptive system:  $K_{SG} = (N_{SG}, E_{SG}, V_{SG}^T, Z_{SG}^T, R_{P_{SG}}, A_{P_{SG}}, D_{SG})$ . Figure 2.6 shows the nodes and edges of this knowledge.

**Scenario** The system starts at  $t_0$  with the actions, the requirements and the context, which also include initial value for the consumption values. Meters send their values at  $t_2$  and  $t_3$ . Based on these data, the load on cables and substation is computed. On  $t_2$ , an overload is detected on the cable, which break the requirement. At the same time point, the system decides to reduce the load of all smart meters. The impact of these actions will be measured at  $t_4$ , *i.e.*, the cable will not be overloaded from  $t_4$ .

**Description of  $N_{SG}$**   $N_{SG}$  is divided into three subset:  $C_{SG}$ ,  $R_{SG}$  and  $A_{SG}$ .  $R_{SG}$  contains one node,  $R_1$  in Figure 2.6, which represents the requirement of this example:  $R_{SG} = \{R_1\}$  Two nodes,  $A_1$  and  $A_2$ , belong to  $A_{SG}$ :  $A_{SG} = \{A_1, A_2\}$ . They represent represent the two actions of this example, respectively decreasing and increasing amps limits. Regarding the context  $C_{SG}$ , there is three nodes to represent the three smart meters ( $M_1$ ,  $M_2$ , and  $M_3$ ), one for the substation ( $S_1$ ), two for the fuses ( $F_1$  and  $F_2$ ), one for the dead-end cabinet ( $D_{C_1}$ ) and one node per consumption value received ( $V_i$ ):  $C_{SG} = \{M_1, M_2, M_3, S_1, F_1, F_2, D_{C_1}\} \cup \{V_i | i \in [1..9]\}$ .

According to the scenario, all nodes are created at  $t_0$  and are never modified, except for nodes to store consumption values. Therefore, their validity period starts at  $t_0$  and never ends:  $\forall n \in A_{SG} \cup R_{SG} \cup \{M_1, M_2, M_3, S_1, F_1, F_2, D_{C_1}\}, V_{SG}^T(n) = [t_0, t_\infty)$ . Considering the consumption values, all the nodes represent the history of the values for the three smart meters. In other words, there is three knowledge element: the consumption measured for each meter. Let  $C_i$  notes the consumption measured by the smart meter  $M_i$ . As shown in Figure 2.6, there is:

- $C_1$  of  $M_1$  is represented by  $\{V_1, V_4, V_7\}$ ,
- $C_2$  of  $M_2$  is represented by  $\{V_2, V_5, V_8\}$ ,
- $C_3$  of  $M_3$  is represented by  $\{V_3, V_6, V_9\}$ .

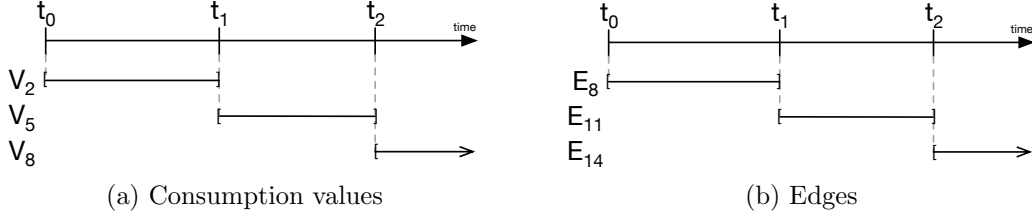


Figure 2.7: Validity periods of the consumptions values and their edges to the smart meter  $M_2$

Taking  $C_2$  as example,  $V_2$  is the initial consumption value, replaced by  $V_5$  at  $t_1$ , itself replaced by  $V_8$  at  $t_2$ . Applying the  $V_{SG}^T$  on these different values, results are thus:

- $V_{SG}^T(V_2) = [t_0, t_1)$ ,
- $V_{SG}^T(V_5) = [t_1, t_2)$ ,
- $V_{SG}^T(V_8) = [t_2, t_\infty)$ .

These validity periods are shown in Figure 2.7a. As meters send the new consumption values at the same time, this example can be also applied to  $C_1$  and  $C_3$ .

From these validity period, the  $Z_{SG}^T$  can be used to navigate to the different values over time. Let's continue with the same example,  $C_2$ . In order to get the evolution of the consumption value  $C_2$ , given the initial one, one will use the  $Z_{SG}^T$  relation:

- $Z_{SG}^T(V_2, t_{s1}) = V_2$ , where  $t_0 \leq t_{s1} < t_1$
- $Z_{SG}^T(V_2, t_{s2}) = V_5$ , where  $t_1 \leq t_{s2} < t_2$
- $Z_{SG}^T(V_2, t_{s3}) = V_8$ , where  $t_2 \leq t_{s3} < t_\infty$ .

**Description of  $E_{SG}$**  In this example, edges are used to store the relationships between the different context elements. For example, the edge between the substation  $S_1$  and the fuse  $F_1$  allow to represent the fact that the fuse is physically inside the substation. Another example, edges between the cable  $C_1$  and the meters  $M_1$ ,  $M_2$  and  $M_3$  represent the fact that these meters are connected to the smart grid through this cable.

One may consider that relations (validity,  $Z^T$ , decisions, action processes and requirements processes) will be stored as edges. But, this decision is let to the implementation part of this formalism.

In our model, only consumption values ( $V_i$  nodes) are modified. Plus, since the

scenario do not imply other edges modifications, only those between meters and values are modified. The edge set contains thus sixteen edges:  $E_{SG} = \{E_i \mid i \in [1..16]\}$ .

By definition, the unmodified edges have a validity period starting from  $t_0$  and never ends:  $\forall i \in [1..7], V_{SG}^T(E_i) = [t_0, t_\infty)$ . The history of the three knowledge elements that represent consumption values do not only impact the nodes which represent the values but also the edges between those nodes and the meters ones:

- $C_1$  impacts edges between  $M_1$  and  $V_1, V_4$ , and  $V_7$ , *i.e.*,  $\{E_8, E_{11}, E_{14}\}$ ,
- $C_2$  impacts edges between  $M_2$  and  $V_2, V_5$ , and  $V_8$ , *i.e.*,  $\{E_9, E_{12}, E_{15}\}$ ,
- $C_3$  impacts edges between  $M_3$  and  $V_3, V_6$ , and  $V_9$ , *i.e.*,  $\{E_{10}, E_{13}, E_{16}\}$ .

Continuing with  $C_2$  as example, the initial edge value is  $E_8$  from  $t_0$ , which is replaced by  $E_{11}$  from  $t_1$ , itself replaced by  $E_{14}$  from  $t_2$ . The validity relation, applied on these edges, thus returns:

- $V_{SG}^T(E_8) = [t_0, t_1) = V_{SG}^T(V_2)$ ,
- $V_{SG}^T(E_{11}) = [t_1, t_2) = V_{SG}^T(V_5)$ ,
- $V_{SG}^T(E_{14}) = [t_2, t_\infty) = V_{SG}^T(V_8)$ ,

These validity periods are depicted in Figure 2.7b. As they are driven by those of consumption values ( $V_2, V_5$ , and  $V_8$ ), they are equals.

As for nodes, the  $Z_{SG}^T$  relation can navigate over time through these values. For example, to get the history of the edges between the consumption value  $C_2$  and the meter represented by  $M_2$ , one can apply the  $Z_{SG}^T$  relation as following:

- $Z_{SG}^T(E_8, t_{s1}) = E_8$ , where  $t_0 \leq t_{s1} < t_1$ ,
- $Z_{SG}^T(E_8, t_{s2}) = E_{11}$ , where  $t_1 \leq t_{s1} < t_2$ ,
- $Z_{SG}^T(E_8, t_{s3}) = E_{14}$ , where  $t_2 \leq t_{s1} < t_\infty$ .

**Description of  $R_{PSG}$**  The requirement calls for minimizing overloads. It means that when the system detects at least one overload, for example in cables, it will take counter actions. As the system has prediction capabilities, it will not only check is there is one at the current time  $t$  but also if one will come in the next hour. The pattern will be defined as follow:  $P_{[t, t+15min]}$ . To determine if there is an overload, the system needs to know: the current and future consumption, the current and future topology. The last one is used to compute the loads from the consumption (cf. Section 1.2).



Let's consider that time points are regular and there is one every 15 minutes and that current time is  $t_0$ . The pattern,  $P_{[t_0, t_1]}$ , will thus contain all nodes that are valid between  $t_0$  and  $t_1$  (included):

- all topology nodes between:  $\{S_1, C_1, F_1, F_2, D_{C_1}, M_1, M_2, M_3\}$
- all consumption values between:  $\{V_i \mid i \in [1..6]\}$ ,
- all edges that connected these nodes:  $\{E_i \mid i \in [1..13]\}$

From these values, the loads is computed and the system checks that none will exceed the capacity of the infrastructure (cables, substations, cabinets).

**Description of  $A_{P_{SG}}$**  Now, let us assume that the execution of  $R_{P_{SG}}$  detects an overload on the cable ( $C_1$ ) at  $t_0$ . The system decides to reduce the amps limits, and thus the load, on the three meters. The action  $A_1$  (decreasing amps limits) is thus executed three times: one time per meter. For each of these action, the input context will correspond to the pattern used by the requirement relation:  $P_{[t_0, t_1]}$ . The output context will contain the predicted values after the actions have been executed. Here, the actions are executed in parallel and their execution time is in seconds. So the impact will be visible from  $t_1$ . So the output pattern contain the three values at  $t_1$ :  $P_{[t_1, t_1]}$ . In summary:

- Action 1:  $A_{P_1} : P_{[t_0, t_1]} \rightarrow P_{[t_1, t_1]}$ ,
- Action 1:  $A_{P_2} : P_{[t_0, t_1]} \rightarrow P_{[t_1, t_1]}$ ,
- Action 1:  $A_{P_3} : P_{[t_0, t_1]} \rightarrow P_{[t_1, t_1]}$ .

**Description of  $D_{SG}$**  Following the scenario, there is one decision,  $D_{SG_1}$ , which try to achieve the requirement  $R_1$  by executing the actions  $A_1$ :  $A_{P_1}$ ,  $A_{P_2}$ , and  $A_{P_3}$ . Then, here the decision is equals to:  $D_{SG_1} = \{R_1, A_{P_1}, A_{P_2}, A_{P_3}\}$ .

**Summrarize** Through this section, I explified how the formalism can be used to define an adaptation decision on a smart grid system. As the decision contains information about the circumstances and the impact, one may use it to debug the process and/or try to explain the behavior of such systems.

# 1 Modeling the knowledge

2 In order to simplify the diagnosis of adaptive systems, this thesis proposes a novel  
3 **metamodel** that combines, what I call, design elements and runtime elements. Design  
4 elements abstract the different elements involved in **knowledge** information to assist  
5 the specification of the adaptation process. Runtime elements instead, represent the  
6 data collected by the adaptation process during its execution. In order to maintain  
7 the consistency between previous design elements and newly created ones, instances  
8 of design elements (*e.g.*, actions) can be either added or removed. Modifying these  
9 elements would consist in removing existing elements and creating new ones. Combining  
10 design elements and runtime elements in the same model helps not only to acquire  
11 the evolution of system but also the evolution of its structure and specification (*e.g.*  
12 evolution of the requirements of the system). Design time elements are depicted in  
13 gray in the Figures 2.8– 2.11. Note that, this thesis does not address how runtime  
14 information is collected.

15 For the sake of modularity, the **metamodel** has been split into four packages: Knowl-  
16 edge, Context, Requirement and Action. All the classes of these packages have a com-  
17 mon parent class that adds the temporality dimension: *TimedElement* class. Before  
18 describing the Knowledge (core) package, I detail this element. Then, I introduce in  
19 more details the other three packages used by the Knowledge package: Context, Re-  
20 quirement, and Action. In below sections, I use "*Package::Class*" notation to refer to  
21 the provenance of a class. If the package is omitted, then the provenance package is  
22 this one described by the figure or text.

## 23 Parent element: *TimedElement* class

24 I assume that all the classes in the different packages extend a *TimedElement* class.  
25 This class contains three methods: *startTime*, *endTime*, and *modificationsTime*. The  
26 first two methods allow accessing the validity interval bounds defined by the previously  
27 discussed  $V^T$  relation. The last method resolves all the timestamps at which an element  
28 has been modified: its history. This method is the implementation of the relation  $Z^T$   
29 described in our formalism (cf. Section ??).

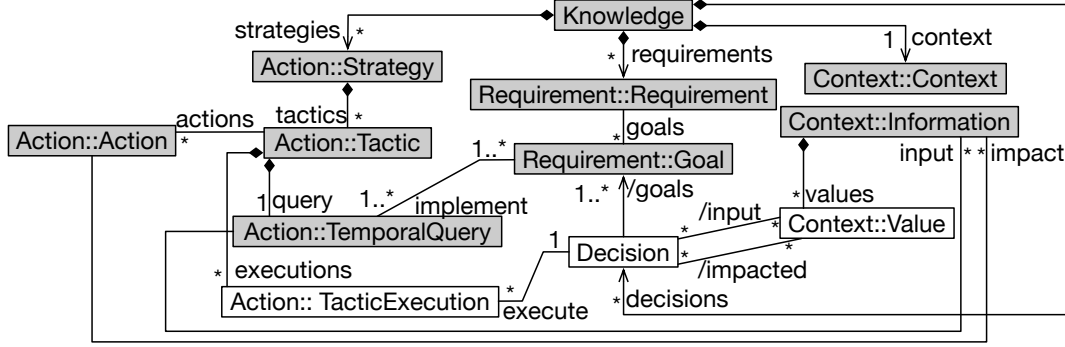


Figure 2.8: Excerpt of the knowledge metamodel

## 1 Knowledge metamodel

In order to enable interactive diagnosis of adaptive systems, traceability links between the decisions made and their circumstances should be organized in a well-structured representation. In what follows, I introduce how the **knowledge metamodel** helps to describe **decisions**, which are linked to their goals and their context (input and impact). Figure 2.8 depicts this **metamodel**.

Knowledge package is composed of a **context**, a set of **requirements**, a set of **strategies**, and a set of **decisions**. A **decision** can be seen as the output of the Analyze and Plan steps in the **Monitor, Analyze, Plan, and Execute over knowledge (MAPE-k)** loop.

Decisions comprise target *goals* and trigger the execution of one *tactic* or more. A decision has an *input* context and an *impacted* context. The context impacted by a decision (*Decision.impact*) is a derived relationship computed by aggregating the impacts of all actions belonging to a decision (see Fig. 2.11). Likewise, the *input* relationship is derived and can be computed similarly. In the smart grid example, a decision can be formulated (in plain English) as follows: since the district D is almost overloaded (*input context*), we reduce the amps limit of greedy consumers using the “*reduce amps limit*” action in order to reduce the load on the cable of the district (*impact*) and satisfy the “*no overload*” policy (*requirement*).

As all the elements inherit from the *TimedElement*, we can capture the time at which a given decision and its subsequent actions were executed, and when their impact

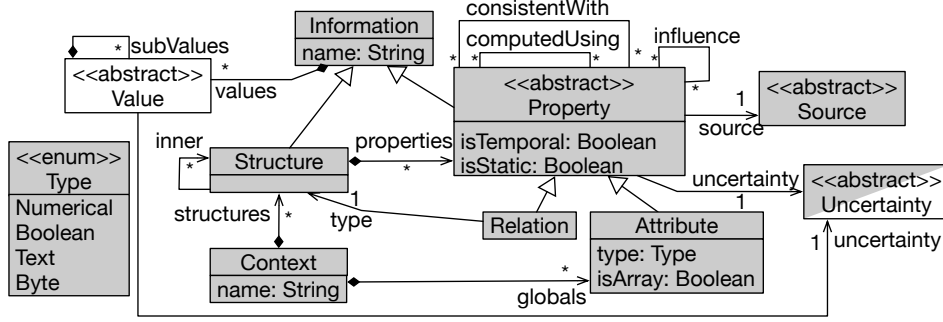


Figure 2.9: Excerpt of the context metamodel

1 materialized, *i.e.*, measured. Thanks to this metamodel representation, a developer can  
 2 apprehend the possible causes behind malicious behavior by navigating from the context  
 3 values to the decisions that have impacted its value (*Property.expected.impact*) and the  
 4 goals it was trying to reach (*Decision.goals*). In Section **TODO: add reference**, we  
 5 present an example of interactive diagnosis queries applied to the smart grid use case.

## 6 Context metamodel

7 Context models structure context information acquired at runtime. For example,  
 8 in a smart-grid system, the context model would contain information about smart-grid  
 9 users (address, names, etc.) resource consumption, etc.

10 An excerpt of the context model is depicted in Figure 2.9. I propose to repre-  
 11 sent the context as a set of structures (*Context.structures*) and global attributes (*Con-*  
 12 *text.globals*). A structure can be viewed as a C-structure with a set of properties  
 13 (*Property*): attributes (*Attribute*) or relationships (*Relation*). A structure may contain  
 14 other nested structures (*Structure.inner*). Structures and properties have values. They  
 15 correspond to the nodes described in the formalization section (*cf.* Section ??). The  
 16 connection feature described in Section 2.1.2 is represented thanks to three recursive  
 17 relationships on the Property class: *consistentWith*, *computedUsing* and *influence*. Ad-  
 18 ditionally, each property has a source (*Source*) and an uncertainty (*Uncertainty*). It  
 19 is up to the stakeholder to extend data with the appropriate source: measured, com-  
 20 puted, provided by a user, or by another system (*e.g.*, weather information coming

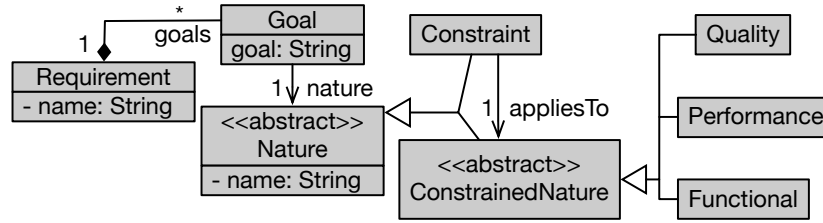


Figure 2.10: Requirement metamodel

1 from a public API). Similarly, the uncertainty class can be extended to represent the  
2 different kinds of uncertainties. Finally, a property can be either historic or static.

### 3 Requirement metamodel

4 As different solutions to model system requirements exist (*e.g.*, KAOS [dardenne1993goal],  
5 i\* [yu2011modelling] or Tropos [DBLP:journals/aamas/BrescianiPGGM04]),  
6 in this metamodel, we abstract their shared concepts. The requirement model, de-  
7 picted in Figure 2.10, represents the *requirement* as a set of *goals*. Each goal has a  
8 *nature* and a textual specification. The nature of the goals adheres to the four cat-  
9 egories of requirements presented in Section 2.1.2. One may use one of the existing  
10 requirements modeling languages (*e.g.*, RELAX) to define the semantics of the require-  
11 ments. Since the requirement model is composed solely of design elements, we may rely  
12 on static analysis techniques to infer the requirement model from existing specifications.  
13 The work of Egyed [egyed01] is one solution among others. This work is out of the  
14 scope of the paper and envisaged for future work.

15 In the guidance example, the requirement model may contain a **balanced resource**  
16 **distribution** requirement. It can be split into different goals: (i) *no overload*, (ii) *no*  
17 *production lack*, (iii) *no production loss*.

### 18 Action metamodel

19 Similar to the requirements metamodel, the actions metamodel also abstracts main  
20 concepts shared among existing solutions to describe adaptation processes and how they  
21 are linked to the context. Figure 2.11 depicts an excerpt of the action metamodel. I de-  
22 fine a strategy as a set of tactics (*Strategy*). A tactic contains a set of actions (*Action*).

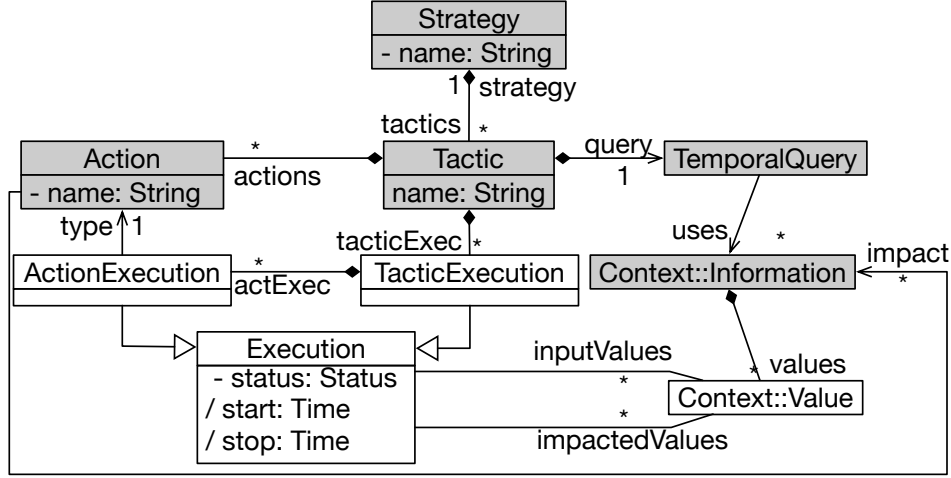


Figure 2.11: Excerpt of the action metamodel

1 A tactic is executed under a precondition represented as a temporal query (*Temporal-*  
2 *Query*) and uses different data from the context as input. In future work, we will inves-  
3 tigate the use of preconditions to schedule the executions order of the actions, similarly  
4 to existing formalisms such as Stitch [DBLP:journals/jss/ChengG12]. The query  
5 can be as complex as needed and can navigate through the whole knowledge model.  
6 Actions have impacts on certain properties, represented by the *impacted* reference.

7 The different executions are represented thanks to the *Execution* class. Each ex-  
8 ecution has a status to track its progress and links to the impacted context val-  
9 ues(*Execution.impactValues*). Similarly, input values are represented thanks to the  
10 *Execution.inputValues* relationship. An execution has *start* and *end* time. Not to con-  
11 fuse with the *startTime* and *endTime* of the validity relation  $\mathcal{V}^T$ . Whilst the former  
12 corresponds to the time range in which a value is valid, the *start* and *stop* time in the  
13 class execution correspond to the time range in which an action or a tactic was being  
14 executed. The start and stop attributes correspond to the relation  $\mathcal{X}$  (see Section ??).  
15 These values can be derived based on the validity relation. They correspond to the  
16 time range in which the status of the execution is "RUNNING". Formally, for every  
17 execution node  $e$ ,  $\mathcal{X}(e) = (\mathcal{V}(e) \mid e.status = "RUNNING")$ .

18 Similarly to requirement models, it is possible to automatically infer design elements

1 of action models by statically analyzing actions specification. Since acquiring informa-  
2 tion about tactics and actions executions happens at runtime, one way to achieve this is  
3 by intercepting calls to actions executions and updating the appropriate action model  
4 elements accordingly. This is out of the scope of this paper and planned for future  
5 work.

## 6 **Validation**

## 7 **Conclusion**





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## <sup>1</sup> Abbreviations

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<sup>2</sup> **MAPE-k** Monitor, Analyze, Plan, and Execute over knowledge. <sup>26</sup>, *Glossary*: **MAPE-**  
<sup>3</sup> **k**



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## 1 Glossary

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2 **action** “Process that, given the **context** and **requirements** as input, adjusts the system  
3 behavior”, IEEE Standards [iso2017systems]. 14

4 **circumstance** State of the **knowledge** when a **decision** has been taken. 15

5 **context** In this document, I use the definition provided by Anind K. Dey [DBLP:journals/puc/Dey01  
6 “Context is any information that can be used to characterize the situation of an entity.  
7 An entity is a person, place, or object that is considered relevant to the interaction  
8 between a user and [the system], including the user and [the system] themselves”. 14,  
9 19, 26

10 **decision** A set of **actions** taken after comparing the state of the **knowledge** with the  
11 **requirement**. 15, 26

12 **knowledge** The knowledge of an adaptive system gathers information about the **con-**  
13 **text**, **actions** and **requirements**. 14–16, 25, 26

14 **MAPE-k** A theoretical model of the adaptation process proposed by Kephart and  
15 Chess [DBLP:journals/computer/KephartC03]. It divides the process in four  
16 stages: monitoring, analysing, planning and executing. These four stages share a **knowl-**  
17 **edge**. 26, *Abbreviation:* MAPE-k

18 **metamodel** Through this thesis, I use the definition of Seidewitz: “A metamodel  
19 is a specification model for a class of [system under study] where each [system un-  
20 der study] in the class is it-self a valid model expressed in a certain modeling lan-  
21 guage.” [DBLP:journals/software/Seidewitz03] . 25, 26

1 **requirement** “(1) Statement that translates or expresses a need and its associated  
2 constraints and conditions, (2) Condition or capability that must be met or possessed  
3 by a system [...] to satisfy an agreement, standard, specification, or other formally  
4 imposed documents”, IEEE Standards [iso2017systems]. 14, 26