COSMOS

Cultivate resilient smart Objects for Sustainable city applicatiOnS

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Table of Acronyms

Acronym	Meaning
API	Application Programming Interface
CB	Case Base
CBR	Case Based Reasoning
CEP	Complex Event Processing
CIDN	Collaborative Intrusion Detection Networks
CRUD	Create Read Update Delete
D	Deliverable
DIKW	Data Information Knowledge Wisdom
DNA	Dynamic Network Analysis
FM	Friends Management
GUI	Graphical User Interface
GVE	Group of Virtual Entities
ID	Identifier
IoT	Internet of Things
IT	Information Technology
KB	Knowledge Base
KM	Knowledge Management
K-NN	K-Nearest Neighbor
KPI	Key Performance Indicator
M2M	Machine-to-Machine
MAPE-K	Monitoring Analyzing Planning Executing-Knowledge
ORMS	Open Reputation Management Systems
P2P	Peer-to-Peer

RBR	Rule-Based Reasoning
REST	Representational State Transfer
SA	Social Analysis
SIoT	Social Internet of Things
SNA	Social Network Analysis
SPARQL	Simple Protocol and RDF Query Language
T&R	Trust & Reputation
TTL	Time To Live
URI	Uniform Resource Identifier
VANET	Vehicular Ad-hoc Networks
VE	Virtual Entity
WP	Work-Package
WSN	Wireless Sensor Network
XML	Extensible Markup Language
XP	Experience
Y	Year

1. Introduction

The Internet of Things (IoT) is very challenging as it leads to networks connecting a huge number of Things that operate on different administrative domains. The scale and the complexity of the formed networks require new approaches that will make objects able to cooperate in an open and reliable way. Taking into consideration the rate at which IoT devices are deployed and used in different applications, one of the main challenges refers to the efficient and optimized management of these entities. Future internet applications tend to exploit a big number of devices, which highlights the need for **distributed management approaches** given that centralized mechanisms are either non efficient (for a huge number of Things) or not applicable (e.g. due to communication problems). Furthermore, the Things are owned and operated by different administrative domains, thus centralized approaches in many cases cannot be used for their management given the diversity in access rights. What is more, management decisions usually do not take into account the context under which the Things operate (e.g. a specific Thing may be used with different configuration parameters in different applications). Approaches are required that will allow management decisions to incorporate situational awareness and propose management actions based on them. Finally, an additional challenge with respect to IoT management relates to the **autonomous reasoning** of Things on a context-aware basis. Autonomous management will integrate different types of knowledge (e.g. device-specific, situational, application-specific, administration-related etc) and trigger decisions accordingly.

In order to face all these challenges, WP5 will provide a framework for the **decentralized and autonomous management of Things** based on principles inspired by **social media technologies**. The integration of social networking concepts into IoT systems is a burgeoning topic of research that promises to support novel and more powerful applications.

In the next section, we present the main tools we can provide to Things to make them more knowledgeable and cognitive. In Section 3 we elaborate on the basic decentralized discovery mechanism we have developed. Section 4 and 5 analyze the ontologies created within the COSMOS project and the main mechanisms for the registration of VEs. In section 6 we present the social approach that the COSMOS project introduces in order to achieve enhanced services like discovery, recommendation and sharing between Things enriched with social properties. Section 7 discusses some of the main concepts regarding Network Runtime Adaptability (part of Task 5.3 which started in the beginning of Y2). Section 8 summarizes the services provided by the functional components of WP5. Finally, in section 9, through the description of an application, we attempt to show-case our framework as a whole.

2. Knowledgeable and Cognitive Virtual Entities

2.1. The concept of Knowledge and Cognition in COSMOS

The IoT will create a flood of real world information to the virtual world. Future applications will be considerably enriched, as they will be more and more aware of what happens in the real world, in real time, everywhere. With a trillion sensors [1] embedded in the environment, all connected by computing systems, software and services, the future IoT platforms have to deliver data and information management mechanisms to handle the exponentially increasing "born digital data". The transformation of this huge amount of raw data into knowledge is one of the biggest challenges behind the IoT. There is an entire cycle of data processing up to the generation of cooperative knowledge networks. These knowledge networks can feed complex hierarchical feedback control loops, since sensorial data is very important for decision making. Decisions made on the virtual side can be reflected on the real environment helping us to better use our resources. Hence, a first step to designing the general architecture of a project on the IoT domain and realizing its capabilities and chances for evolution is the definition of its own **Knowledge Management (KM) cycle**. Knowledge management is the process of capturing, developing, sharing and effectively using knowledge and summarizes all activities with the goal of using knowledge in a more efficient and effective manner, achieving certain objectives. A **Knowledge Pyramid**, the **DIKW Pyramid** [2], is usually used for the representation of purported structural and/or functional relationships between **data (D)**, **information (I)**, **knowledge (K)** and **wisdom (W)**. Generally, when we take data and put it in context we have information, when information becomes actionable it is transformed into knowledge and when pieces of knowledge are consolidated, with the help of experience, wisdom is born.

In our DIKW Pyramid, Data are the raw-data which are collected from the VEs through their IoT-services. Physical objects like buses or houses which are represented by VEs will have a huge number of embedded sensors, continuously "feeding" COSMOS with data regarding the temperature and humidity of the environment, the velocity of the buses etc. Information is the result produced by analyzing the raw-data. Suitable mechanisms make possible the detection of simple or complex events of the physical world around the VEs. For example, analyzing the data offered by the sensors of the buses or the houses, the detection of events like "fire" or "traffic" becomes possible. Knowledge includes problems or situations detected (e.g. "fire") associated with specific solutions, implemented through IoT-services. In other words, Knowledge includes directions that specify how the VEs are going to react in changes of their environment in a well-defined way. For example, a house may include in its **Knowledge Base (KB)** the scenario of the problem "fire" and "know" that the solution to the problem is "inform the fire department". Knowledge is a store of information proven useful for a capacity to act. This level gives the VEs the advantage of learning from previous experiences. Finally, Wisdom is born using high-level reasoning techniques, such as **Case Based Reasoning (CBR)** [3] and Rule Based Reasoning [4], which give to the VEs the ability to reason and understand their situation and take decisions on their own, thus producing Knowledge on their own. Things attaining this level could be characterized as cognitive, intelligent or wise, as they have the capacity to acquire, adapt, modify, extend and use knowledge in order to solve problems.

For a Thing to be autonomous, its corresponding Virtual Entity should be equipped with **1)** its own Knowledge Base and **2)** a **cognition loop**, a cognitive process that can perceive its current conditions, plan, decide, act on those conditions and learn from the consequences of the actions, all while following end-to-end goals. The issue of the knowledge representation and the reasoning technique used for this cognition loop is discussed in the rest of section 2.

2.2. The concept of Cases

The proposed approach provides the VEs with the advantage of learning from previous experiences. Experience is usable knowledge acquired through the use of collaborating communication techniques between two or more individuals. Different types of experiences are defined, arising from the correlated phases of our control loop approach, which is adopted for the implementation of the project regarding VEs' management. Experience can be a piece of knowledge described by an ontology, a model resulting from Machine Learning or contextual information. However, we focus mainly on the representation of experience through **Cases** as defined in the CBR technique.

A case can be considered as a combination of a **Problem** with its **Solution**, whereas a problem consists of one or more **Events** or **Goals** (State Vectors). In other words, a case is a kind of rule for an actuation plan, which is triggered when specific events are identified [5].

Each VE may maintain its own **Case Base (CB)** locally as part of its KB. Storage of experience in a local or central KB [6] depends on whether the individual's knowledge needs are constant or opportunistic. Such a categorization of needs will be primarily based on the "domain" membership of individual VEs as well as technical limitations that may be present. A KB can be shared between VEs with suitable social characteristics, something that improves the decision making mechanisms. Moreover, VEs representing weak devices that do not have their own KB can take advantage of the KB of their social group.

2.2.1. Description of Problems

Taking under consideration that the State Vectors constituting the Problems may describe current or future situations that a VE has to face, there are basically two definitions of what a problem is. The first one is event driven while the second one is goal driven.

- **Event driven:** The Problems consist of Events that have to be identified (e.g. by a local mini-CEP engine or the central COSMOS CEP engine) to trigger the Solution. This description of Events may for example be linked with the corresponding Topics of the COSMOS Message Bus. The problem can be simple (one Event) or complex (a list or sequence of Events).
- **Goal driven:** The Problems consist of Events describing the current situation of the VE as well as Goals that describe a desired deviation from the current state, in other words, a desired future situation. Yet again, the Solution is triggered by the Events. However, in this case, the Solution can be evaluated in an autonomous way (and not by human-users necessarily) as the expected/desired final state can be used by a feedback loop.

2.2.2. Description of Solutions

Generally, a Solution is a list or sequence of actions (actuations) to be undertaken given an initial state in order to reach a final state where the Problem has "disappeared" (Events) or has been solved (Events and Goals). Moreover, the Solution could contain some extra information regarding the actions undertaken (e.g. the description of the final state in case we study an Event driven Problem and not a Goal driven one).

In the case of COSMOS, in its simplest form, a Solution can be the **URI of an IoT-service** which provides some kind of actuation. Of course, more advanced solutions should contain some "logic" like algorithms. A Solution can be primitive (1 task- IoT-service) or complex (list or sequence of IoT-services). Three types of solutions have been identified:

- **Type 1** - Solutions that are just a **recommendation service**, a **message**: For example, the Solution to the Problem *"fire"* (detected as a complex Event by the CEP) at a VE-house could be just a message sent to the user, saying "The roof, the roof, the roof is on fire! Call the fire department!". This Solution can be shared between similar VEs facing similar Problems, without having to be changed. Moreover, since there is no kind of actuation regarding the physical world (we don't open/close doors/windows etc.) these scenarios are the safest.
- **Type 2** - Concrete Solutions that consist of **IoT-services from 3rd party VEs**: In the same scenario, the VE-house facing the Problem *"fire"* will actuate the IoT-service (through its URI) *"send request to the VE-fire department"*. This solution can yet again be shared between similar VEs (similar means that they have close geographic location too) with no serious issues. A VE2-house that will take this Solution will inform the same VE-fire department by using the very same URI.
- **Type 3** - Generic Solutions that consist of **IoT-services provided by the VE itself or 3rd party VEs and need some logic**: Now, if the VE1-house uses as a Solution a URI that represents the IoT-service *"open MY (of VE1) doors"*, it is evident that this Solution cannot be shared with other VEs for this scenario. Obviously, a VE2-house has to use the IoT-service *"open MY (of VE2) doors"* and it should not try to open the doors of VE1. This means that the **structure/logic** of the Solution has to be shared in this case. As a result, the **generic description of IoT-services** becomes necessary.

Regarding the 3rd type of Solutions, this kind of generic description of IoT-services should be defined by the application itself (like the rest types of solutions). In this case, the **Execution/Actuation level** would consist of replacing the generic fields ("I, Vex, need an IoT-service that is mine and has these characteristics and three IoT-services from other VEs that have these characteristics") with concrete ones. The developing the semantic description of the Applications in parallel is necessary.

A scenario were VEs share between them Solutions of Type 1 and 2 has already been demonstrated during Year 1. Achieving to demonstrate a scenario where generic Solutions are shared and used by VEs is one of our main future goals.

2.2.3. Cases Representation

In order to use the previous experiences in the CBR cycle (section 2.3.1), Cases must be represented in a structural manner. Several methods of representation can be used in case-based reasoning and the choice of a representation method depends on the domain that the system is modeling and the types of similarity assessments and retrieval which are chosen according to the requirements of the system. The simplest format to represent the cases in the case base is to have simple feature-value vectors which are good for cases with attributes of nominal or numeric values. Some techniques of structural-based representation [7] are the object-oriented based method, the spreading activation method, the generalized cases method, the graph-oriented method and the ontology-based method. More information about these techniques is available in the previous deliverable.

COSMOS uses ontologies for the description of many entities like the VEs, the IoT-services and the Applications, consequently, using the same type of representation for the Cases of the VEs is not a far-fetched thought. Ontologies provide a rich vocabulary for the general domain knowledge enabling the users or application developers to better express their requirements and submit queries, leading to greater precision and recall rates. Moreover, formalization of ontologies improves retrieval and similarity adaptation and learning, concepts that will be discussed later. That is why the **ontology-based representation** has been chosen and used.

Now that we have analyzed the concept of Cases and the method of their representation, we can provide an example of the structure of a Case. Let's take a scenario where the owner of a flat, while away from it, wants to set its internal temperature to a certain degree, before he/she arrives to it. Thus, he/she notifies the corresponding VE-flat by using a COSMOS-enabled Application and provides as input i. the desired temperature and ii. the estimated time of arrival to the flat. This is a problem regarding energy management where we want the desired temperature to be achieved right before the owner arrives to the flat. The Cases that will be produced and used by the Application could have as a Problem the inputs of the user and the current situation of the house (room temperature before) and as a Solution the URI of the IoT-service that corresponds to the actuation of boiler and the required input. In the Case depicted at the following figure, the boiler should be set to 32 °C.

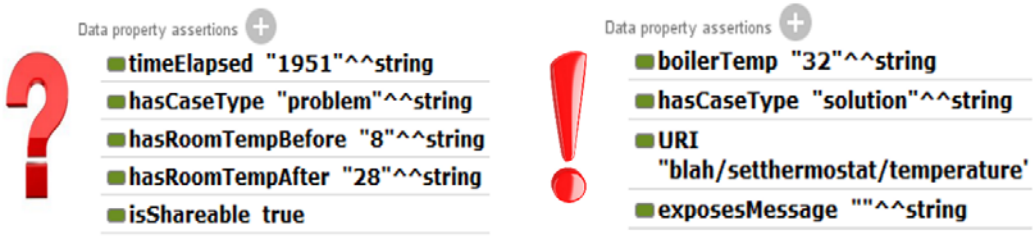


Figure 1: Example of the semantic description of a Case.

2.2.4. Case Memory Models

CBR is going to be one of the tools that COSMOS will provide to enable VEs run Applications. Whenever a VE "downloads" a COSMOS-enabled Application, a set of initial Cases is provided by it and stored in the CB of the VE. While the VE is facing new Problems related to this Application, new Cases are created as it will be described later.

The CB should be organized in a manageable structure that can support efficient search and retrieval methods. Several groups of case memory models have been proposed like the Flat Memory model, the Hierarchy or Shared-Feature Network Memory model and the Network Based Memory Models, like the Case Retrieval Nets model and the Category Exemplar model.

As a first approach, during Year 1, the **Flat Memory model** was adopted. In a Flat Memory model, all the Cases are organized at the same level. Retrieval time in this memory organization is very high since for each and every retrieval all the Cases in the CB must be compared to the target Case. Thus, this method is unacceptable for large CBs. However, advantages of this approach which include maximum accuracy and easy retention have led to its use in many applications.

The CBs of the VEs are not going to be big. However, the fact that each VE as many categories of Cases as are the Applications it runs means that we could use another memory model which would lead to lower retrieval times, the **Category Exemplar model**. The case memory in this model is a network structure of categories, semantic relations, cases and index pointers. This organization has three types of indices: feature links which point from problem features to a case or a category, case links that point from a category to its cases and difference links which point from categories to the neighbor cases where the differences to the current category are small. In this organization, the categories are interlinked within a semantic network that represents a background of general domain knowledge which supports having explanation for some CBR tasks. Then the evolution of the organization of the CBs of the VEs to this direction is one of our main future goals.

2.3. Reasoning Technique: CBR

By studying carefully several reasoning techniques, Case-based Reasoning was chosen as the most appropriate reasoning approach for the case of COSMOS. Case-based Reasoning is the process of solving problems based on past experience. In more detail, it tries to solve a Case by looking for similar Cases from the past and reusing the Solutions of these Cases to solve the current Problems [3]. The case of using a different reasoning approach at a higher level (forming a hybrid reasoning approach) will also be studied later in the project. Indicatively, CBR reflects human reasoning and is the easiest approach for the Application developers and the one that can be used in a huge variety of domains. Moreover, the concept of adapting past solutions is one of the main requirements of COSMOS. In that sense, the Cases produced via CBR become the Experience of the VEs, which can not only aid to the planning of future solutions, but can also be shared between different VEs as it will be described later. One of the main disadvantages of CBR (store/compute trade-offs because of large CBs) is tackled, as most of the VEs are going to have their own light-weight CB.

As it has been described in the previous deliverable, the functional component that enables the VEs to use CBR is the **Planner** (a Reasoner). The Planner will become part of the VEs during their registration time and will run locally.

2.3.1. The CBR cycle

In 1994, Aamodt and Plaza [3] proposed a life cycle for CBR systems to make evident the knowledge engineering effort in CBR. This cycle is used by other CBR researchers as a framework and consists of four main parts; **retrieve, reuse, revise** and **retain**. Each of these parts includes a set of tasks and different methods have been proposed for each of them. A brief presentation of the four phases of the CBR cycle follows:

1. **Retrieve**: Retrieve the most similar Case or Cases to the new one, in other words, given a target Problem, retrieve from the memory Cases relevant to solving it.
2. **Reuse**: Reuse the retrieved Cases by copying them completely or by integrating the Solutions of the Cases retrieved.
3. **Revise**: Revise or adapt the Solution(s) of the Cases retrieved trying to solve the new problem. Having mapped the previous Solution to the target situation, test the new Solution in the real world (or a simulation) and, if necessary, revise.
4. **Retain**: Retain the new Solution once it has been proven that it is correct and brings successful results. Store new Case and found Solution into CB.

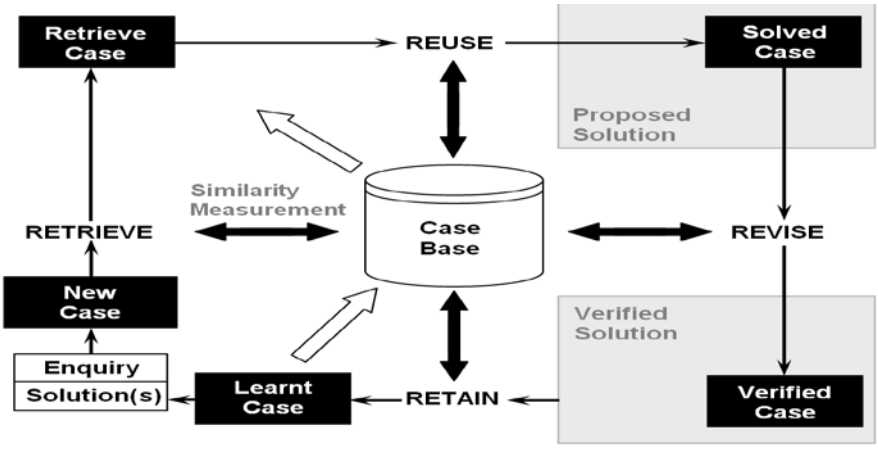


Figure 2: The CBR cycle.

2.3.2. The stage of Retrieval

CBR is based on finding Solutions to new Problems by reusing older Cases. As a result, the only component needed besides the CB in order to achieve CBR at its simplest form is a reasoner (the Planner) that can identify **similarities** between Cases.

Every **retrieval method** is a combination of **a)** a **similarity assessment procedure**, which determines the similarity between a target Case and a Case in the CB and **b)** a **procedure for searching the case memory** to find the most similar Cases. A retrieval method used by the COSMOS Planner has been defined:

- Regarding the similarity assessment procedure, in order to measure similarity between Cases, we follow two steps:
  - ✓ First of all, the similarity of the attributes of the new Case (that consists of a Problem and no Solution) with the various Cases in the CB has to be measured. The method used takes as input the names of the parameters of a new incomplete Case and the percentage of acceptable similarity. The similarity is calculated by using the **Jaccard similarity coefficient** [8].
  - ✓ If there are Cases in the CB that have sufficiently similar attributes to those of the new Case, the Planner class is calculating a new similarity index in order to find the most appropriate Case. This method takes as input a list of the names of the attributes describing the new Case, a list of the values of the attributes, a list of the weights of these attributes (if any) and a new similarity threshold regarding the values of the attributes and returns the most appropriate Solution. In this case, the dissimilarity is calculated by using the **Bray-Curtis distance** [9].
- Regarding the procedure for searching the case memory, the retrieval technique that was chosen is the **simple flat memory k-Nearest Neighbor retrieval (K-NN)** [10]. In this approach, the assessment of similarity is based on a weighted sum of features.

It should be noted that if the Category Exemplar model is chosen as a Case Memory model in the future, the retrieval method will have to change. Since each new Case will be the result of a specific Application (e.g. Application 1), it would be compared only with the Cases that belong to the category “Application 1”. That means that the first step of the similarity assessment procedure may become unnecessary, lowering the retrieval times. Moreover, the procedure for searching the case memory may also have to change.

2.3.3. Evaluation of Cases and Feedback loops

In a case base reasoning system learning is done in the retention step. In this step, the new Case will be added to the CB according to some policies in the system. Retention includes adding knowledge and new Cases to the CB, which need to be indexed, as well as deleting cases from the CB in order to restrict its growth. In order to choose whether a new Case should be stored or not, its evaluation is necessary, and evaluation can take place if feedback loops are available.

There are four main issues that have to be discussed in order to define a feedback loop:

- **Who** will give the feedback? The feedback may come from **a)** the **system** itself through an autonomic loop (e.g. by comparing the initial Problem with the final state) or **b) human-users**. In the first case, the Executor should trigger the Monitoring component as described in the previous deliverable and the corresponding logic should be added to the Application.
- **When** will the evaluation take place? Feedback may be given **a) before** or **b) after** the execution of the Solution. Evaluation from the system can take place after the actuations of course. Evaluation from human-users can take place both before and after the execution of

the Solution. It should be noted that in many scenarios where the execution of the Solution will result in the usage of actuators, for safety reasons, feedback may have to be given by human-users before this execution.

- **What** will be evaluated? There are some factors that can be evaluated only by the system and other factors that can be evaluated only by human-users. For example, the exact temperature of a heated room can be evaluated according to a schedule by the system, but the comfort that a human feels inside the room can be evaluated only by human-users.
- **How** will the evaluation take place?
  - ✓ For feedback given by human-users, the **five-star rating system** can be used.
  - ✓ For feedback coming from the system, two mechanisms can be used depending on the nature of the Problem. If the Problem is **event-driven**, then the Solution is considered successful when the corresponding Event is no longer detected (e.g. Event "fire"). If the Problem is **goal-driven**, then the Solution is considered successful when the corresponding Goal (desired situation) is reached or unsuccessful if the desired situation has not been reached after a predetermined amount of time.

2.4. Types of Learning

VEs have three types of learning cycles which are complementary and may occur in parallel [11]. These may interact with each other in complicated ways and are the following:

- **individual learning:** Individual learning will take the form of Cases creation and storage inside the VEs. By utilizing sensor readings and actuation values, each VE is capable of creating complete Cases of a complexity proportional to its technical abilities. The individual enrichment of the local CB can serve as a basis for the second stage of learning.
- **learning through communication:** This second stage comes into play when the locally stored knowledge is not sufficient for the needs of a VE. In this case, a VE uses the experience sharing (XP-sharing) service and targets a group of Friends that may have the required knowledge. This procedure is further analyzed in section 3.
- **learning through a knowledge repository:** Finally, if both previous knowledge acquisition mechanisms fail, VEs possess the ability to connect to a central KB. It is worth mentioning that experience, as a final resort, could be stored centrally in the COSMOS repositories so that a "purge" of acquired knowledge does not result in loss of experience.

If we want to experiment on the concept of CBR, we can choose to focus on the first and third option. By adding the second option, we produce a Social IoT system. This system is further described in the next sections.

2.5. Functionalities of the Planner

2.5.1. Retrieval modes

COSMOS will offer various services to the Application developers giving them the opportunity to define CBs and CBR cognition loops in order to build their own COSMOS-enabled Applications. COSMOS could provide a GUI template consisting of fields to fill in, in order, for example, to describe the Problem and give the input for the similarity calculation. The developer could define data for the simple attributes of a Case and weights for its complex attributes. The entered information would then be retrieved to build Cases, while integrating their semantics. The developers should also be able to define the logic of their Applications, the corresponding feedback loops needed, how the Cases are going to be stored in the CBs etc.

Each VE will have its own Planner and CB and will be able to facilitate M2M communication. The Planner of the VEs acts as part of a MAPE-K loop (hence in an autonomous way) as well as "manually", in other words, on demand. Consequently, the Planner has two retrieval modes:

- The Planner uses complete cases (Problem and Solution is defined). That means that it follows the changes on the Topics that correspond to specific Problems. When the Planner gets notified by other components, the corresponding solution is forwarded to the Executor.
- The Planner can accept as input a target Case (a case with the description of the Problem only) and create a new complete Case. That means that the Planner has to find similar cases in its CB or the CBs of other VEs, choose the most appropriate Solution(s) and create new solutions (e.g. services composition).

Both of these modes were demonstrated during the first review of the project by the two demos presented by WP5. In the first demo, the Planner of a VE-house was following Topics of the COSMOS Message Bus regarding sensor malfunctions and was reacting to them, while in the second demo, the Planner was reasoning on Problems defined by the end-user who wanted to set the temperature of his/her house at a specific degree after a specific amount of time (see Figure 1).

2.5.2. Levels of self-governance

CBR is a simple and flexible yet powerful reasoning technique when it is used at the right domains. As such it can be used for many purposes. Moreover, the persistent nature of the ontologies used enables proactiveness and robustness to 'ignorable events' while their unitary nature enables end-to-end adaptations. These characteristics enable the VEs to achieve high levels of self-governance. In 2002, IBM announced a new autonomic deployment model that outlines a staged approach for helping customers chart a course towards establishing an autonomic IT environment [12]. This autonomic deployment model defines five levels of increasingly sophisticated self-governance of systems: Basic, Managed, Predictive, Adaptive, Full Autonomic. The Planner can reach all three last levels depending on the definition and the usage of the Problems and the Solutions. That way, a VE using a Planner can be:

- **Adaptive:** The VE can not only provide advice on actions, but can automatically take the right actions based on the information that is available to it on what is happening in its surroundings.
- **Full-autonomic:** The operation of the VE is governed by business policies and objectives (expressed by Goals).
- **Predictive:** This characteristic has not been presented yet and is the outcome of a "peculiar" usage of the Cases. The VE itself can begin to recognize patterns, predict the optimal configuration and provide advice on what course of action the administrator should take, as well as predict the outcome of certain actions. For example, if the Problems of some Cases include both Events and Goals, then the VE could predict that by taking certain actions (described by Solutions) after an initial state has been recognized (Events) then the result will be the Goals. In this case, the Planner would create an incomplete Case consisting of an incomplete Problem (Events only) and a Solution and would search for similar Cases to find the Goals (which in this situation would be the predicted future state).

2.5.3. System or COSMOS Cases and self-management

For each Application a distinct set of Cases will be created and stored in the CB of a VE. However, the Planner and the CBR cycle can be used beyond the domain of application specific scenarios focused on the end-users. They can also be used for the self-management of the (COSMOS) system itself. The COSMOS community could identify weaknesses and fails of the system and create **System Cases** (**COSMOS Cases**) to solve them. An example is given below.

As it will be described later, an infinite loop during XP-sharing is avoided because of the introduction of TTL. However, if the request somehow returns to the initial VE, there is no meaning for the VE to forward the request again, since the very same VEs will be reached. This problem can easily get solved by updating the mechanism via adding a name/identifier each request. Then the initial VE (if it has any pending requests) will check whether an incoming request is its own or not. In case it is, then it will not forward the request again.

This **update** could take place if the VEs were to change their source-code of the XP-sharing component. A disadvantage of this approach is that this kind of update could make the service unavailable for a while. However, because of the Planner, there is a second option. This update could be forwarded to the VEs not as a change in the code of their functional components but a change in their CB: new Cases. In the case we are studying, the triggering Problem would be the action of a) sending or b) receiving an XP-sharing request. The Solution would be a) adding a field in the request with an identifier and marking the request as a pending request or b) checking this field from a forwarded request and deciding whether it should be reforwarded or not. Of course, this specific mechanism will be added at the source code since it has already been identified. Another simple example is the case were the COSMOS platform has to inform the VEs that they should change their TTL from e.g. 6 to 5, because of a massive registration of new VEs to the network.

This new kind of Cases could use a more sophisticated classification of the Cases based on the different self-management attributes that the different Cases implement. The classification that could be adopted is the one used for control loop functionalities in self-managing autonomic systems [13]:

i. **Self-Configuring Cases:** Cases for the self-configuration of the components of the VE adapting dynamically to changes in the environment, using policies provided by the IT professionals. Such changes could include the deployment of new components or the removal of existing ones.
ii. **Self-Optimizing Cases:** Cases enabling components to monitor and tune themselves automatically. The tuning actions could mean reallocating resources—such as in response to dynamically changing workloads—to improve overall utilization, or ensuring that particular business transactions can be completed in a timely fashion.
iii. **Self-Healing Cases:** Cases enabling components to detect system malfunctions and initiate policy-based corrective actions without disrupting the IT environment. Self-healing can be implemented in two different styles (reactive and proactive). In reactive the system detects and recovers from faults as they occur and tries to repair the faulted functions if possible. In proactive the system monitors its state to detect and adjust its behavior before reaching an undesired state.
iv. **Self-Protecting Cases:** Cases enabling the system to defend against internal and external threats, which can be accidental (e.g. cascading failures) or malicious.

Thus, the System Case presented in the previous example can be characterized as a Self-Configuration/Optimization Case. Generally, System Cases can be used to control critical parameters of the system (such as the TTL).

2.5.4. The Planner as a generic Ontologies Comparator

Because of the way we designed the Planner, it can be used generally as an **Ontologies Comparator**. That means that the Planner can be used for other services beyond the comparison of Cases that is described in the previous subsections. In other words, the Planner can reason on other parts of the Knowledge Base too, as long as ontologies are used, using parts of the very same retrieval procedure.

In COSMOS, ontologies are used for the semantic description of VEs, IoT-services, Applications etc. If such descriptions are stored locally, the Planner can be used for answering to queries regarding these entities. Let's take as an example the problem of the 3rd type Solutions presented in subsection 2.2.2. These Solutions consist of generic descriptions of IoT-services. The Planner could reason on its local IoT-services Base in order to find IoT-services of the VE with specific characteristics, replacing that way generic fields of these Solutions with concrete ones. The importance of this functionality of the Planner can be better understood in the next section.

CBR is naturally applicable to web services. A service case can be defined as w = (d, s) and consists of the service description d and its service solution (or functions) s as well as other information including functional dependency among web services. Web service retrieval, reuse, adaptation and retention in web services correspond easily to the CBR cycle. Our Planner can be involved into a unified approach for case-based web service **discovery**, **recommendation** and **composition**. Osman et al. [14] present an approach that uses CBR for modeling dynamic Web service discovery and matchmaking. Lajmi et al. [15] propose an approach called WeSCo CBR that aims at enhancing the process of Web service composition by using a CBR technique. In [16] Fouad and Baghdad present an approach to dynamically produce composite services (Figure 3).

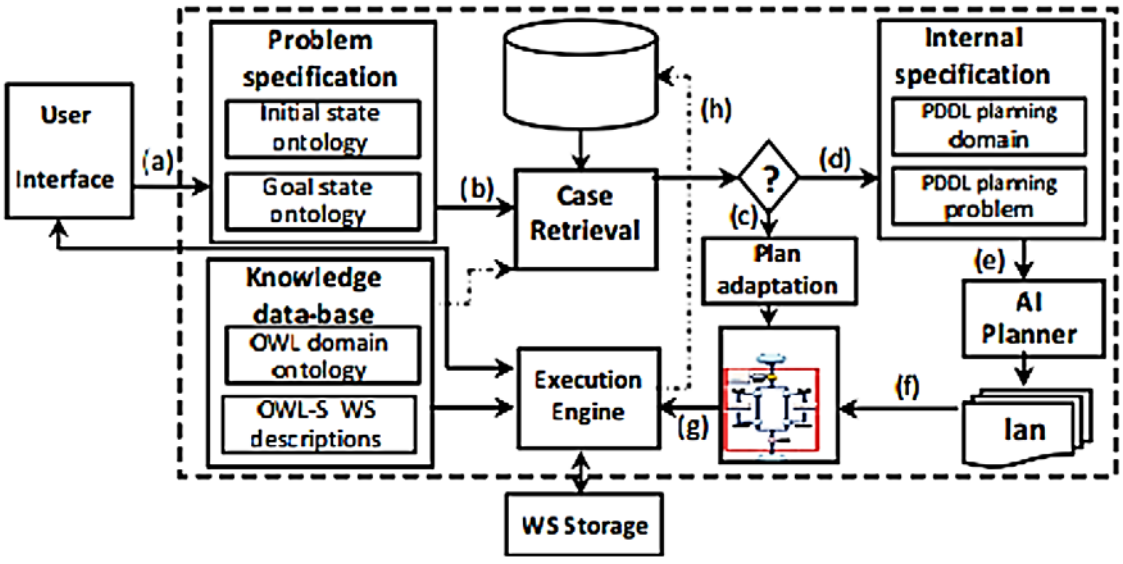


Figure 3: Producing Composite Services with CBR.

3. Decentralized Discovery in Distributed Systems

3.1. Cases Discovery - Learning through Communication

The concept of adapting past solutions is one of the main requirements of CBR. For this reason, we introduce the idea of allowing VEs to share their Cases, thus producing an environment where the knowledge is distributed and knowledge flow is supported. In that sense, the Cases produced via CBR become one form of Experience of the VEs, which can not only aid in the planning of future solutions, but can also be shared between different VEs. Because of the great distribution of the knowledge among the VEs, the development of decentralized discovery mechanisms becomes essential.

Learning through communication comes into play when the locally stored knowledge is not sufficient for the needs of a VE (Figure 4A for VE I). Such needs may be constant or opportunistic in nature, a distinction which helps segregate the actions taken on the provided knowledge. In this case, a VE uses the **experience sharing (XP-sharing) service** and forwards its request for new knowledge to a group of other "friendly" VEs (**Friends**) that may have the required knowledge. Friends are maintained **Friend Lists** in the KB (one Friend List for each Application). The request contains the description of the Problem (**parameter names and values**) for which the VE needs a Solution, the **threshold values** for the corresponding similarity indexes and a **TTL number** (see subsection 3.3).

Upon receiving the request, a Friend extracts the data and checks the value of the TTL number (Figure 4B for VE I). If after reducing it by 1 the TTL number is above zero, then the Friend uses its Planner in order to check if a similar Problem to the requested one exists inside its own local CB. In case a similar enough Problem is found, the Friend returns to the initial VE the similarity percentage of the similar Problem (or the similar Problem itself) and the corresponding Solution (parameter names and values, URIs, Messages etc).

If a similar Problem is not retrieved, then the Friend may become a "broker" by initiating recursively a new call of the XP-Sharing mechanism (Figure 4C for VE I). Therefore brokers are dynamically designated taking into account that Friends are willing and able to act as such for their respective Friends. This approach is related to the "six degrees of separation" concept that has become quite popular at the domain of social networks [17].

All of the similar Cases that are found are forwarded back to the initial VE only through its direct Friends. In order to be possible for the initial VE to evaluate the answers coming from Friends of Friends, the ID of the VE from which a similar Case is found may be part of the answer to the XP-sharing request. The Planner chooses the best Case amongst the similar Cases. However, the procedure followed for choosing the best Case is not the same with the one followed during individual learning. During learning through communication, the Planner takes under consideration not only the **similarity indexes** of the Cases but also the **social indexes** of the VEs that provided these Cases. For this to happen, **weights** for similarity and social indexes must be defined. In other words, the best Case is the one that has a similar Problem to the initial request and derives from a **trustworthy VE**. The matter of the trustworthiness of VEs is discussed in subsection 6.3. Finally, through feedback loops, the selected Solution is evaluated and the same happens through the **Social Monitoring** component for the VEs from which this Solution was shared (Figure 4D for VE I). Social Monitoring is analyzed in subsection 6.1.

As a final note, the technical solution used for learning through communication involves RESTful interfaces [17] that connect individual VEs on a peer to peer basis.

Learning through communication was successfully demonstrated during the first review of the project.

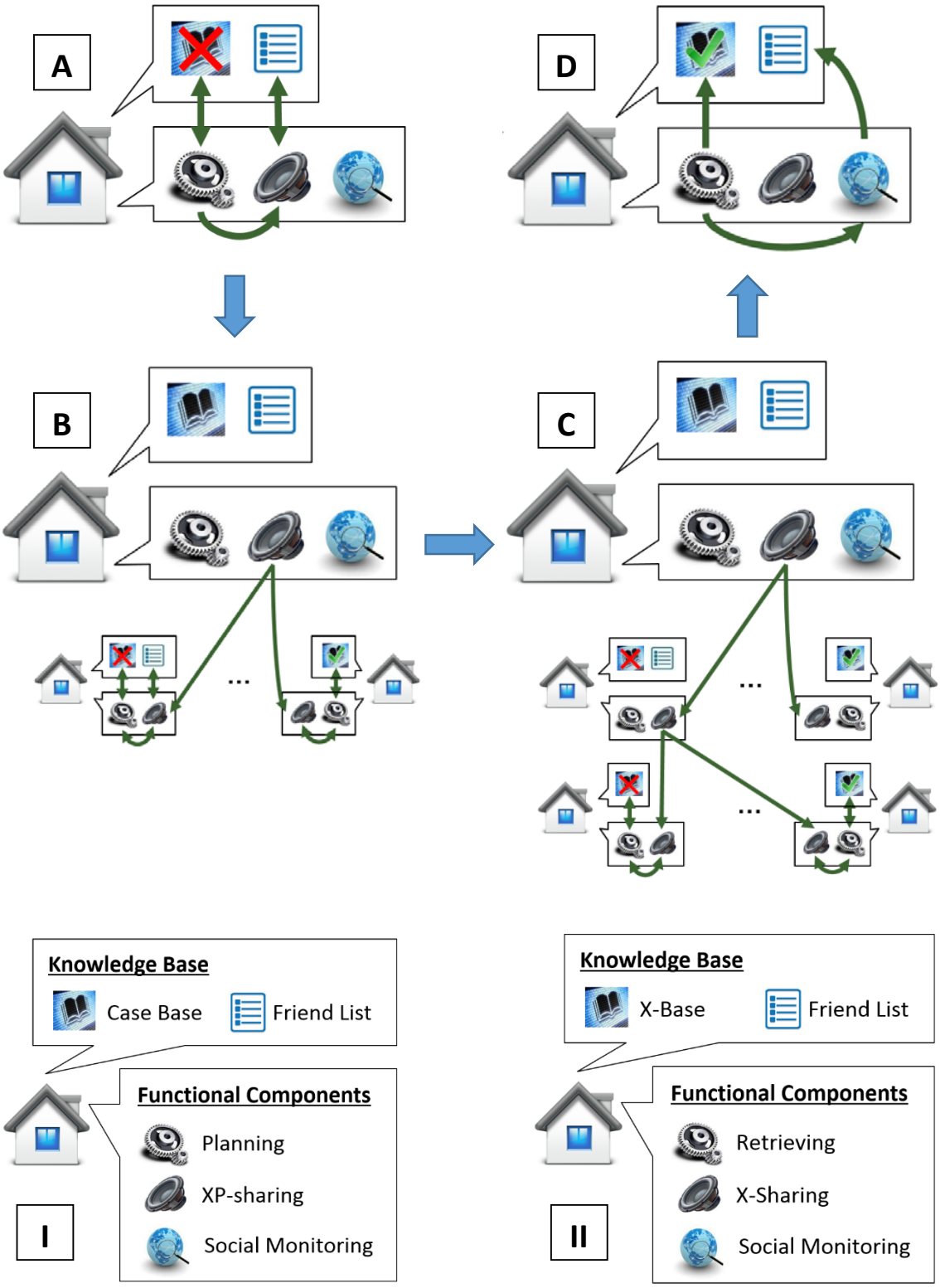


Figure 4: Decentralized Discovery mechanism.

3.2. Discovery of other entities

As it is discussed in subsection 2.5.4, the Planner can reason not only on Cases, but on other parts of the Knowledge Base too, as long as ontologies are used. Because of this characteristic of the Planner, the mechanism used for the decentralized discovery of Cases can be extended to the discovery of IoT-services, VEs, Applications, Friends or any other entities. This is depicted in Figure 4for VE II, were the Planner acts as a simple Retriever.

For each Application based on the CBR technique that a VE uses, the VE should maintain a separate Friend List. The Friends contained to these lists should be similar to the VE. However, in the case of discovery of other entities besides Cases, it is evident that **a)** the usage of one (per VE) **general Friend List** is enough and **b)** the Friends populating this list do not have to be similar to the VE. The criteria taken under consideration for the selection of Friends used for discovery or other purposes are further analyzed in subsection 6.2.2.

3.3. Issues regarding the Discovery Request

When a VE decides to initiate the experience sharing mechanism with its Friends, it specifies the "depth" of communication. That is important mainly because of the recursive way the experience sharing method works, meaning that if a Friend of the original VE does not locate a suitable case inside its own local CB, it will check the depth required (mentioned TTL/time-to-live of the experience query) and initiate a new version of experience sharing this time directed at its own Friends. Thus, we ensure that the entire process will operate until either a suitable solution has been discovered or until it reaches a dead end (TTL time out, no case present in our friend VE cluster).

For each one of the discovery mechanisms described previously, one of the main goals is refining their recursive abilities. A big step in this direction is the use of the TTL number not only as a static although customizable input but as an actual dynamic representation of the in-between stages of "information brokering" based on the theory of the six degrees of separation and the actual social capabilities of affected VEs. When a TTL number is high and the recursive discovery uses nodes (broker VEs) with many outward connections, this can lead to **network overhead**, a situation we want to avoid. If we take into account social criteria of the VE we can adjust the TTL number. For example, by initially using a simple mathematical function of a logarithmic nature, we can adjust the TTL number of each kind of discovery request by using the **number of Friends** (of the corresponding Friend List) of a VE as well as a "target audience" to be reached (**maxhits** variable). Further code development and experimentation with real data will refine the function used. Moreover, if the experimental data points to such a possibility, we will use an absolute upper limit for TTL in the sense of the six degrees of separation theory.

Although the TTL number can solve the problem of network overhead and makes sure that the creation of infinite loops is not possible when the initial request is forwarded back to the initial VE (through e.g. Friends of Friends), it does not solve the problem of **"discovery overlap"**. If a discovery request somehow returns to the initial VE, there is no meaning for the VE to forward the request again, since the very same VEs will be reached. This problem can easily get solved by adding a name/identifier for each request. Then the initial VE (if it has any pending requests) will check whether an incoming request is its own or not. In case it is, then it will not forward the request again.

It is worth noting that when a VE accepts a Case discovery request, then it retrieves only Cases in its local CB that are marked as **shareable** by flags. These flags can be set either by the corresponding Application developer or the owner of the VE.

3.4. Types of Communication

We can make a distinction between two forms of learning through communication:

- **supply driven learning:** In supply driven learning, an individual VE acquires new experience and communicates it to the Groups of VEs (GVEs) it belongs to.
- **demand driven learning:** In demand driven learning, a VE comes along a new event/problem and asks its Friends whether they have a solution for this problem.

In both cases, two factors should be taken into account:

- **overhead:** the number of useless messages that are acceptable from the recipients side.
- **hit rate:** the amount of VEs that get the message compared to the amount of VEs that should have received it.

Regarding the dissemination mode, there are three options to choose from (adopting the terminology from the advertising, marketing and communications domain):

- **Broadcasting:** Sending the message to every available VE. This way, the hit rate is maximized at the cost of a large communication overhead. An advantage of sending the message to a large audience is that it creates redundancy in the knowledge assets of the system, which facilitates knowledge development through combination. However, for most IoT use-cases, this is not an option due to scalability issues. As such, COSMOS does not provide any broadcasting mechanisms.
- **Narrow casting:** Sending the message to every VE that may be interested in a specific topic. This option combines the advantages of the other two, but it requires the VEs to state beforehand which kinds of messages they are interested in (e.g. by means of a user profile). This in turn requires that there is a predefined set of possible topics or, otherwise, that there are guidelines for creating new topics. In our case, data can flow through the system via a Message Bus which is organized into Topics. Each VE can publish and/or subscribe to them. The whole process is supported by a Complex Event Processing (CEP) component which is responsible for processing data and analyzing them in real time, according to applications' specific logic. If a certain event is detected by the CEP component, this may trigger the generation of certain messages to a new topic.
- **Personal casting:** Sending the message only to VEs that are directly involved to its content. This is the most efficient way of communication, as only VEs that can directly help or can offer the new required knowledge are informed. In this way, the communication overhead is kept to a minimum, which is important for maintaining the communication channel alive. That is why the VEs need Friends and we should develop a social environment that can support their discovery.

4. Ontologies

4.1. The COSMOS Ontology

One of the key goals of COSMOS is to facilitate the development of IoT Applications by providing sharing mechanisms for data, experience, models etc. The main pillar supporting these goals is the VE. VEs extend IoT-services adding new functionalities as well as a social dimension to these services.

One of the requirements which had to be considered was the efficient retrieval and the precise addressability of VE properties. These requirements are enforced also by the fact that different actors are involved in the development and deployment of a COSMOS enabled Application (VE developers, platform owners, platform extension developers, COSMOS Application enabled developers etc.) since resources are shared and reused.

To support these requirements we have decided to use semantic technologies and the linked data paradigm [19] in the description of the COSMOS entities. We have therefore designed the core **COSMOS ontology** which is supplemented with the **social-related Ontology**. Application or domain specific descriptions can also be integrated through **domain specific ontologies**. Figure 5 presents a block diagram of the information model, including the key concepts supported by the COSMOS ontologies.

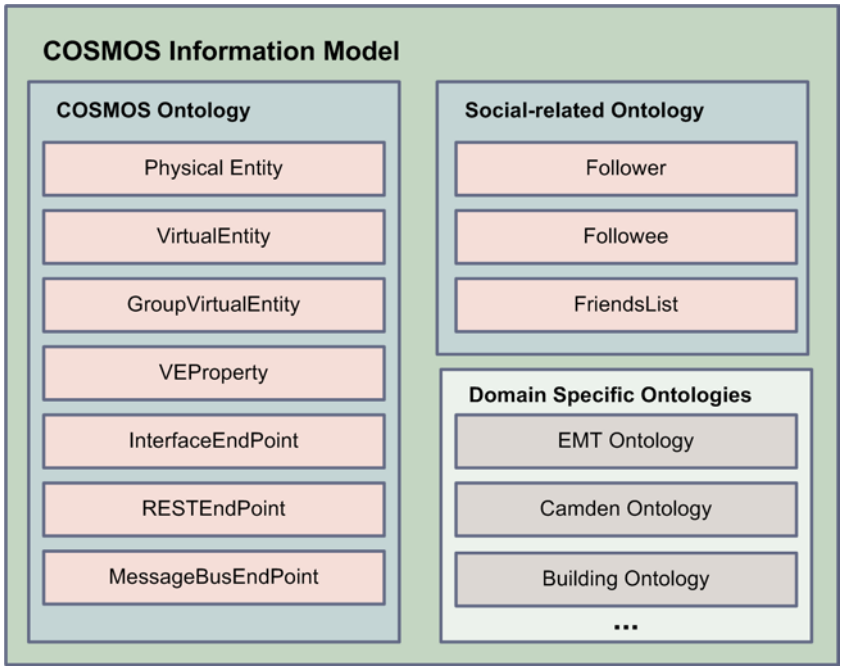


Figure 5: COSMOS Information Model.

The COSMOS ontology is a light weight domain interdependent ontology centered around the description of the VEs. It provides the model for describing the complete chain from physical entities, to resources, IoT-services, VEs and final endpoints. Figure 6 depicts the COSMOS ontology with all the concepts and relations connecting them.

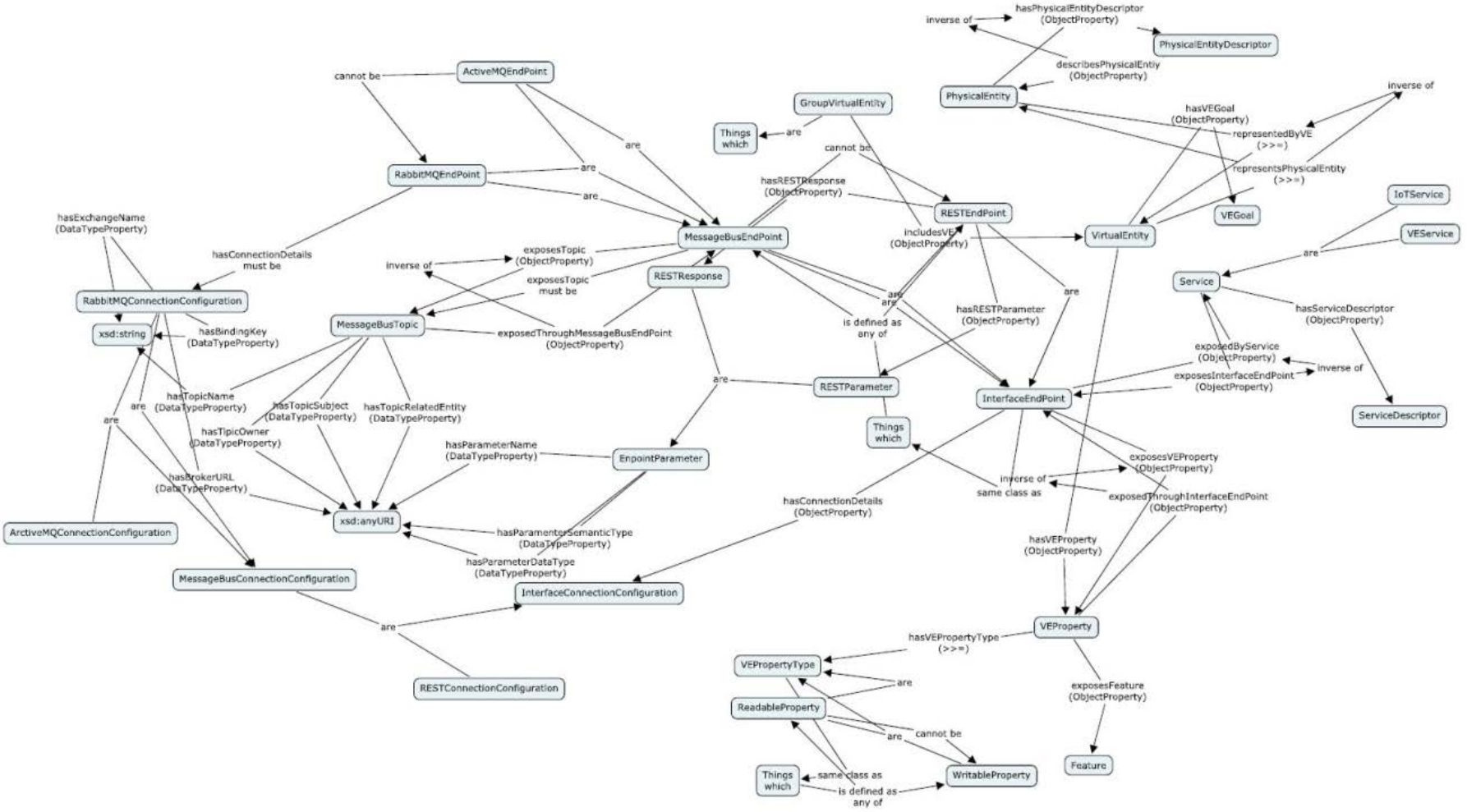


Figure 6: COSMOS Ontology.

In the following paragraphs we will describe the key concepts of the ontology and their relations. Since the complete depiction of the ontology is hard to be followed by the reader, we will depict the ontology in a cloned manner in Figure 7, Figure 8, Figure 9 and Figure 10 meaning that some classes are duplicated in order to facilitate viewing.

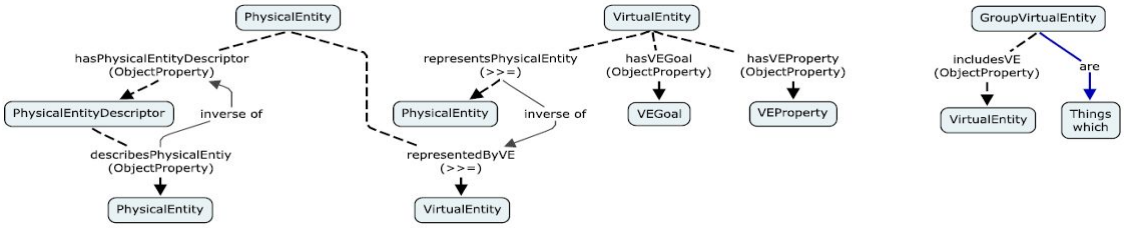


Figure 7: COSMOS Ontology - partial view 1.

VirtualEntity – It represents the key concept of COSMOS and the ontology is centered around it. As already mentioned, a VE provides an abstraction above the IoT-services, encapsulating additional services, social relations and functionalities.

PhysicalEntity – A Virtual Entity represents an entity from the physical world which could be anything; a bus, a building or even a person.

PhysicalEntityDescriptor – A physical entity should have its own descriptor to facilitate its retrieval and uniform means of describing it.

VEProperty – VEs expose values which not only relate to the readings of sensors or the control of actuators but also to additional functionalities which the VE concept introduces. For instance, the physical entity of a bus might be represented by a VE which would expose: current speed, location, number of hard brake events in the last 60 minutes, the condition of the traffic based on situational awareness etc. In other words, the VE is able to expose data which are not necessarily IoT related but the result of an internal computation, the aggregation of external data, a prediction model etc. The VEProperty is the concept providing the bridge between the physical entity, all these features (including also non IoT related aspects) and the actual access interfaces which will be later described. In other words, it references to descriptions of ***what*** is exposed and ***how*** it is exposed.

Feature – As already mentioned, a VE exposes IoT and non-IoT related data. The *feature* concept is meant to describe these capabilities (sensor readings, actuator commands, aggregated data, historical models etc). It indicates ***what*** is being exposed by the VEProperty.

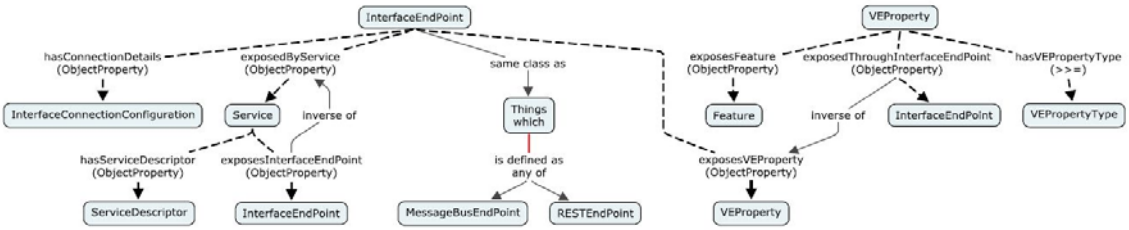


Figure 8: COSMOS Ontology - partial view 2.

InterfaceEndPoint – The concept of *Interface EndPoint* provides the transition from the conceptual description of the VEs to the actual interfaces providing the access to the features exposed by the VE properties. A VE will most probably have multiple VE properties which are exposed by services and have to be uniquely addressable. These can be IoT-services or other kinds of services and their endpoints can be REST endpoints or message bus endpoints.

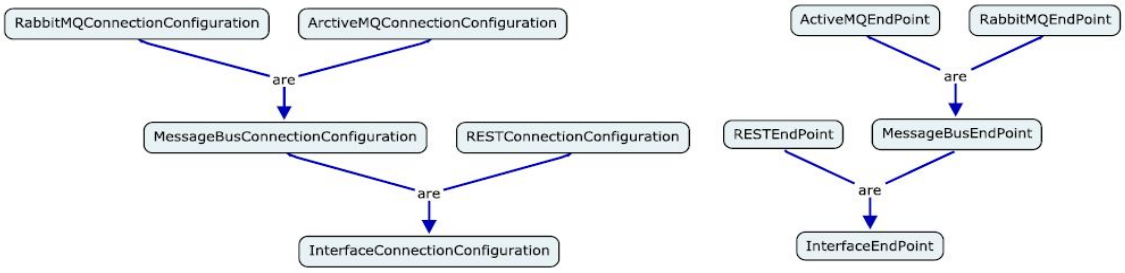


Figure 9: COSMOS Ontology - partial view 3.

The ontology can be extended to support different interfaces. Figure 10 indicates some of the descriptors for different endpoints such as the **RESTEndpoint**, **RabbitMQEndPoint** or **ActiveMQEnpoint**.

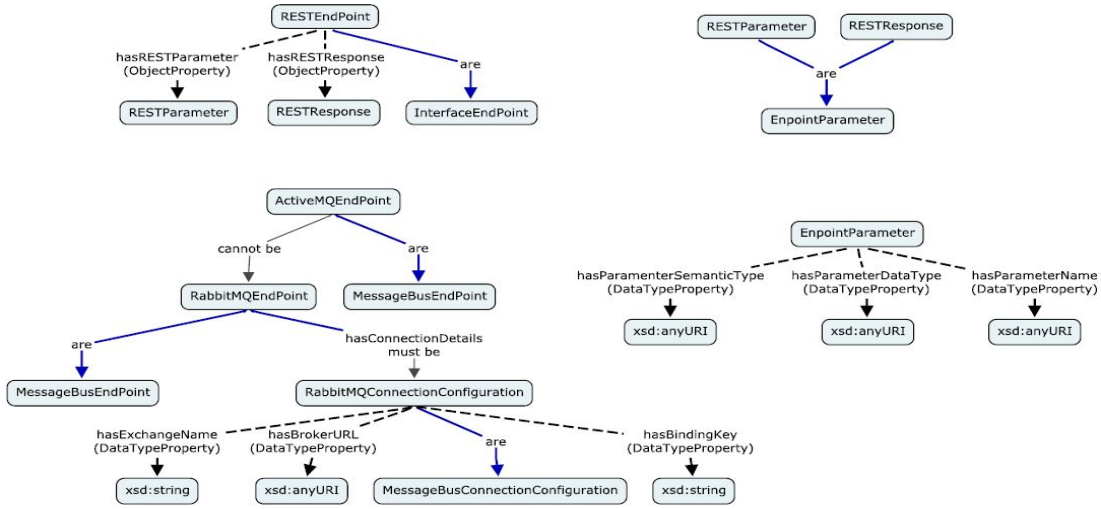


Figure 10: COSMOS Ontology - partial view 4.

As seen from the above descriptions, the ontology is domain independent. The advantage of domain independence is that the ontology will not require any changes which have not been considered during the design whenever a new Application is developed for a use case. In fact, such a goal would have been impossible to achieve since the range of use cases is infinite. Instead, the ontology supports the extension of the VE descriptions using domain ontologies.

4.2. Domain Ontologies

VE descriptions can be augmented through the use of domain specific ontologies. This makes use of the linked data paradigm which is a key concept of the semantic technologies. While the COSMOS ontology is the product of the COSMOS project and is intended to be the main model for the VE description, domain ontologies can be built by VE developers, COSMOS enabled Applications or COSMOS-extensions developers to support the description of their use cases and most probably of the physical entities which their VEs are representing.

While in some use cases new domain specific ontologies will be required, this is a mandatory requirement since in some cases existing ontologies can be reused. In fact, from the perspective of the core COSMOS ontology, there is no constraint regarding domain specific ontologies which are referenced in the VE descriptions. D2.3.2 contains the description of a sample domain ontology which has been built around the EMT use case scenarios.

5. Registry and Centralized Discovery

As already mentioned, proper retrieval of the VEs' and other COSMOS related entities' descriptions is a key requirement for the sharing mechanism.

To support this requirement we have designed a Registry whose role is to provide the adequate functionality for the retrieval of VEs. This Registry is in fact a semantic Registry and is backed by the core COSMOS ontology. Figure 11 depicts a block diagram of the VE Registry with its main components.

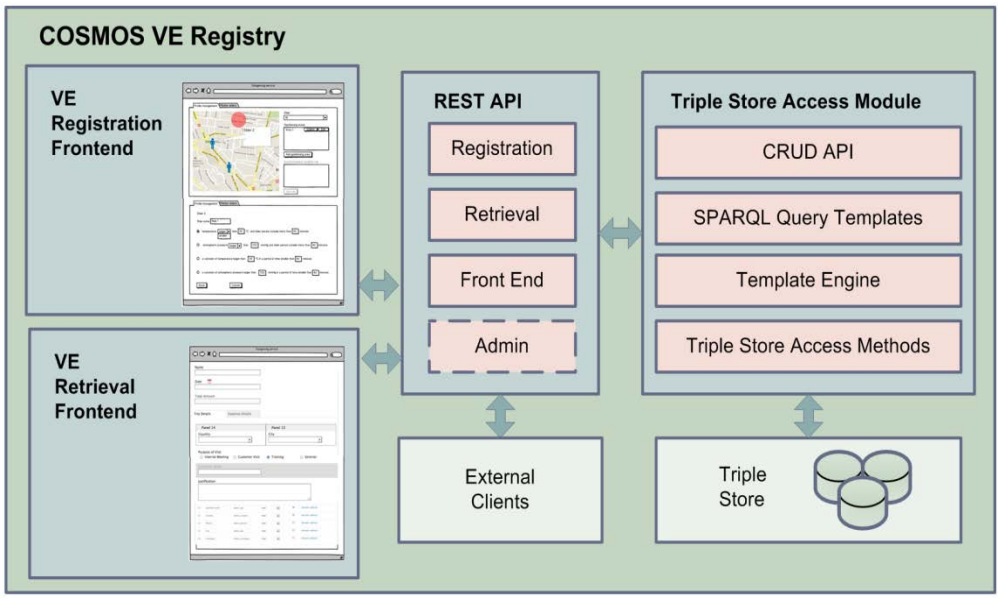


Figure 11: VE Registry block diagram.

While the backing of the COSMOS ontology provides a common "language" for the description of VEs, users are not required to have a thorough understanding of the semantic technologies used in order to describe and retrieve VEs. This is due to the fact that the Registry exposes a front-end which hides the complexity of the publishing and retrieval mechanisms.

The Registry's back-end is responsible for adequate storage, retrieval and maintenance of these descriptions. As also described in deliverable D2.3.2, triple stores provide the support for the persistence of the semantic descriptions made for VEs and other related entities and components. Moreover, the Registry exposes an API which can be used without any knowledge of the underlying technologies. Nevertheless, the exposed REST API also allows external clients (such as other components, Applications, VEs) to connect to the Registry and access its functionalities.

The stores are accessed using SPARQL queries but the complexity of these queries is hidden to the user of the VE Registry. The API provides access to CRUD operations from a higher level (VE description) and handles transparently the triple creation, removal, update and deletion.

6. Social Virtual Entities

The integration of social networking concepts into IoT systems is a burgeoning topic of research that promises to support novel and more powerful applications. In this section we present the social approach that the COSMOS project introduces in order to achieve enhanced services like discovery, recommendation and sharing between Things enriched with social properties. We investigate how typical notions and modes of interactions of social networking can be extended to the networks of Things, providing a Social Internet of Things (SIoT) [20] platform.

6.1. Social Relations & Monitoring

Instead of trying to map various social relations and characteristics of the real world to the IoT, a more concrete approach would be to identify the various interactions that could exist between VEs. As it has been discussed in D5.1.1, VE1 can send to VE2 a **service request** for:

- **XP-sharing**
- decentralized **discovery** of other entities
- access to **IoT-services**
- **recommendations** (analyzed in subsections 6.2.1 and 6.3.3)

Inspired from the social media domain, we define and monitor the following **relations**:

- **Followees:** The VEs that are being tracked by a specific VE. The Followees Lists define the receivers of the VE's requests for services.
- **Followers:** The VEs that track a specific VE. They are held in the Followers Lists and indicate the credibility and reputation of a VE. Moreover, their number can act as a rough indicator of the frequency of requests for services from other VEs.
- **Groups:** To how many GVEs a VE belongs and how many VEs and GVEs (separately and in total) a GVE contains. A VE belonging to many GVEs gives us a measure of its "centrality" in the whole system and the real world, whereas the members of a GVE provide the main data needed to grasp its size and complexity.

The relation between a VE and its Followees is trust-based and non-mutual (low reciprocity [20][20]). This means that VE1 may use the experience of VE2, but on the other hand, VE2 may not do the same for VE1. A VE (**trustor**) trusts blindly its Followees (**trustees**) and requires access to their services.

On the same spirit, examples of **interaction metrics** that are used are:

- **Shares:** How many times a VE has shared its services with other VEs. This value is used as an indicator of the popularity of the VE. However, for a more valuable evaluation, the number of followers, the amount of the shareable resources and the number of the received requests should be taken under consideration.
- **Assists:** How many times a VE has acted as a broker. This value is used as an indicator of the efficient social connectivity of the VE. The concept of Assists is only applicable to requests for XP-sharing and decentralized discovery.
- **Applauses (for Shares and Assists):** How many times the social shares or assists have been regarded as useful from the receivers. This value could be used as an indicator of the trustworthiness and the reputation of the VE. This is a quite important property, but rather difficult to monitor compared to other elements, as feedback regarding the quality of the provided shares/assists is needed.

- **Mentions:** How many times an IoT-service of a specific VE is mentioned in the Case Base of other VEs. This is another indicator of the popularity and reputation of a VE. The concept of Mentions is applicable only to requests for IoT-services.

The interaction metrics (Shares, Assists, Applauses and Mentions) monitored by the Social Monitoring component of a VE are stored locally in the corresponding **Followees Lists**. For each type of service request (XP-sharing, decentralized discovery, IoT-services, recommendations) and for each application, different Followees Lists are created. These metrics are calculated in a distributed manner by the VEs on a per-VE basis and are the main input for the services provided by the **Social Analysis** and **Friends Management (FM)** components. For each metric identified we develop/choose the corresponding Key Performance Indicators (KPIs) and tools that should be imported into the VE during the phase of registration. Based on the chosen configuration, different levels of reporting granularity could be possible in order to keep the monitoring tasks as light-weight as possible but still to be able to perform in depth analysis whenever needed. The events that are generated at the Social Monitoring level can be evaluated at different platform levels (node level, group level or system wide) against a set of rules. The rules, which can be added, deleted or updated at runtime, may be specified by the consumers of information to set and control the flow of events and the aggregation output. It should be mentioned that a quite complex approach is used, as we can monitor how many times two specific VEs have (succesfully) exchanged services with each other. Instead of just monitoring that "VE1 shared its experience 1302 times", if needed, we can know that "VE1 shared its experience with VE2 203 times, with VE3 523 times….".

From these metrics, the **social indexes** of the several kinds of Friends are extracted. These are the **Trust Index** and the **Reputation Index**. More details about these indexes can be found in subsection 6.3. Our main goal is to combine the Reputation Index, the Trust Index and the **Reliability Index** (an absolute indicator of the performance of the corresponding Physical Entity of a VE) of a Followee and express them by only one social measure, the **Dependability Index** of the Followee. This measure, which is further discussed later, is a crucial indicator that will lead a VE to take decisions regarding the selection of new experience or new Followees. If a VE presents good social indexes, then other VEs will keep following it (sending services requests to it). If the social indexes of the same VE worsen (because it has started providing bad services), then the other VEs may decide to remove it from their Followees Lists, place it in a **Black List** and stop following it. This may have as a result even the **social exclusion** of the VE. In this case, if the social indexes of the VE become better, then **social reintegration** will take place, as other VEs will start following the VE once more. The social exclusion and reintegration are a subject of the sensitivity of the actors to good or bad experiences from services. The component responsible for the renewal of the Friends Lists according to these indexes is the Friends Management component.

It is evident that since the social indexes will constantly change, it is quite important to take under consideration their **evolution**. Although a VE may have a low Reputation Index when we study a wide time-window, it may have a much greater Reputation Index when we study a smaller and recent time-window. This means that the specific VE is improving and this improvement should be evaluated fairly by the system and the community. For this reason, for each Followee in each Followees List the **timestamps** (unix time) and the evaluation of the last e.g. 3-10 interactions may be kept, so that, when applying simple rules, the evolution of the indexes can be studied.

The main functionalities of the Social Monitoring component were demonstrated during the first review of the project.

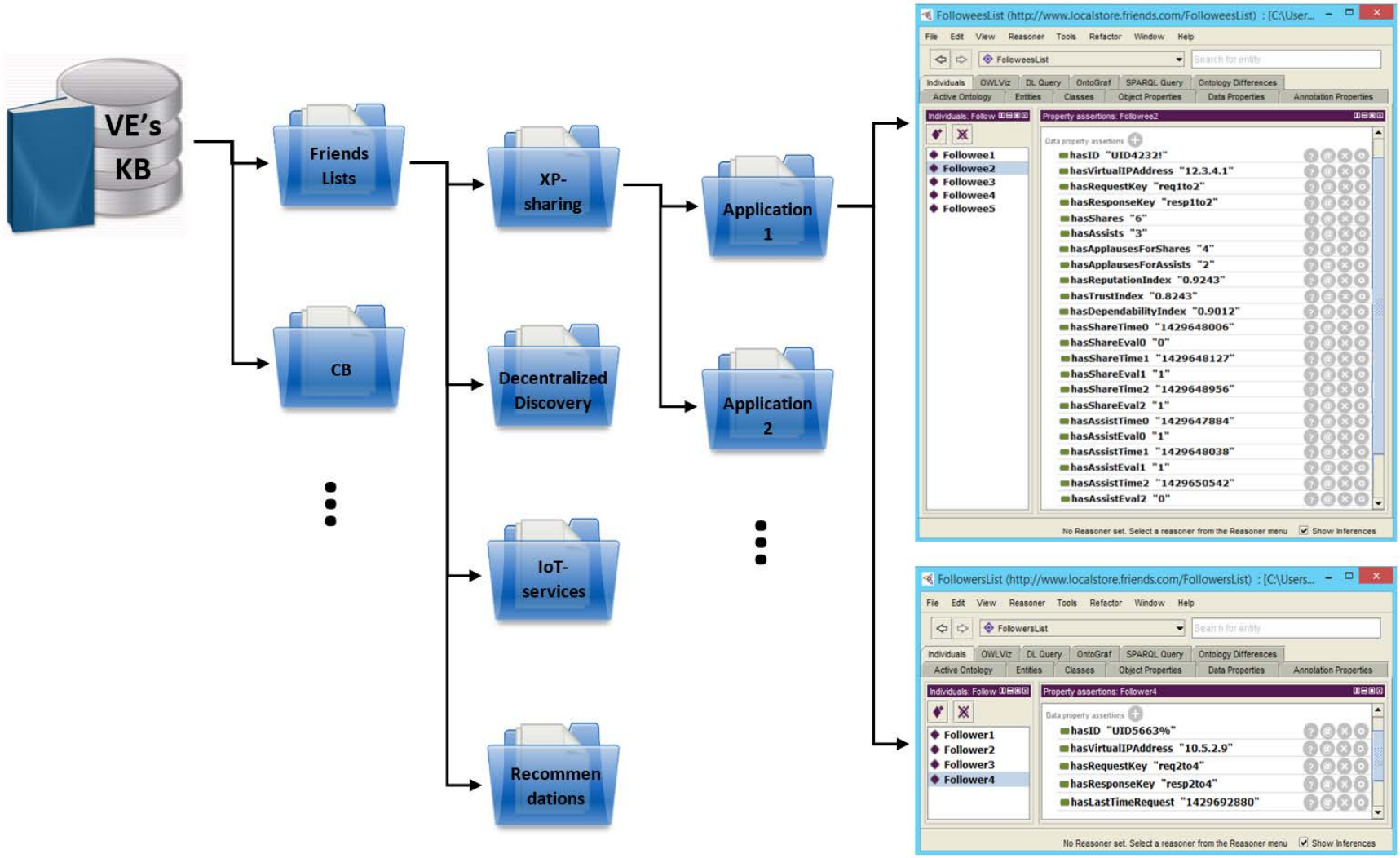


Figure 12: Example of a Followees List and a Followers List of a VE for XP-sharing.

6.2. Social Links Establishment/Recommendations

6.2.1. Followees Acquisition

The process of Followee acquisition begins at the phase of registration. The user can manually set the Followees Lists of the VE (e.g. in order to link his/her VEs with each other). This is the most basic way a VE forms social bonds. Such friends will have a number of benefits during the social monitoring or discovery phases (e.g. greater priority).

Another way of acquiring Followees is through a discovery mechanism, which is always based on recommendation. Discovery through recommendation is more reliable and provides protection from malicious behavior. New Followees can be recommended to a VE by its **current Followees** or by the **Social Analysis component** of the COSMOS platform.

In the first case, transitivity is used. For example, a VE1 recommends to VE2 its own Followees as new Followees. After the VE acquires a number of recommended Followees, it asks its social neighborhood or the SA component for their Trust and Reputation Indexes. The results are forwarded to the FM component of the VE which, based on the thresholds set by the user, decides whether it will accept the new recommendations or not.

In the second case the VE sends a Followee recommendation request to the SA component. Practically, this leads to the renewal of its Followees. The VE's FM sends the request, passing as parameters weights for calculating the Dependability Index a minimum acceptable limit of its value and the current Followees List. The SA calculates the Dependability of the Followees, as it will be described later, based on the above input. If the new indexes are below the limit, the SA purges these VEs from the list, replacing them with more reliable ones and a new Followees List is returned. Followees that have been set by users and do not have high Dependability Index anymore are not thrown away from the Followees List, but are isolated (are not used for requests) till their Dependability Index gets high enough. Recognizing the opportunity of a malicious user trying to 'overvalue' his/her own VEs and therefore create imbalances in the social network through collusion, the platform takes into account the specific social characteristics of the VEs and adds random suitable VEs in their Followees Lists.

To sum up, there are three ways for a VE to acquire Followees:

- through the input of the owners/developers of the VE
- through recommendations from Followees of the VE
- through recommendations from the COSMOS platform.

6.2.2. Recommendation Criteria

The choice of suitable Followees, no matter for which service they will be chosen, is based on three composite criteria: Relevance, Dependability and Structural Power. Relevance aggregates concepts like these of Homophily (Domain and Physical Entity attributes in the VEs' ontologies) and Distance Proximity (Location & GeoLocation), Dependability refers to Reputation, Trust and Reliability, while Structural Power is evaluated by several structural network characteristics. Our goal is to combine all these criteria in order to obtain the "Social Power" of a VE [22].

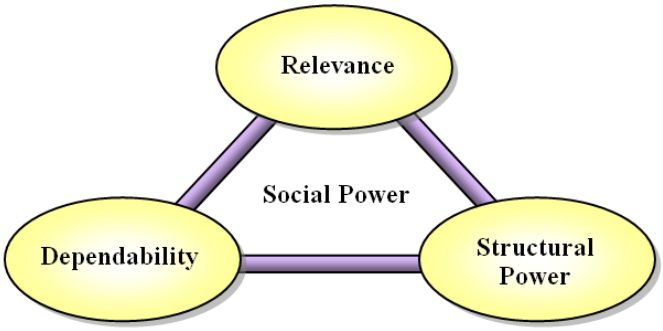


Figure 13: The Social Power of a Followee.

6.2.2.1 Relevance/(Dis)Similarity

The basic criterion for choosing a new Followee, which will most probably provide good and useful services, mainly depends on its similarity (regarding both its nature and its environment) to the VE asking for new Followees. As a result, two properties have to be studied:

- **Homophily/Heterophily:** the degree to which VEs and GVEs form ties with similar/dissimilar others. Similarity can be based on domain-dependent characteristics of the VEs as they are described in their ontologies. Homophily leads to the formation of homogeneous groups, where the relationships are easy to build. However, for VEs associated with more domains, heterophily is desirable. These two aspects aim at providing more beneficial friend recommendation services. For example, the homophily value is taken under consideration from friend recommendation services when the requests concern XP-sharing. In the case of requests concerning IoT-services or Decentralized Discovery, the opposite characteristic, the heterophily value, is extracted. In general, various recommendation algorithms could be developed incorporating both values [23].
- **Propinquity:** The tendency for VEs to have more ties with geographically close others. The mobility of Things should be taken under consideration [24].

6.2.2.2 Dependability

The Dependability Index of VE can be calculated from: **i.** other VEs by taking under consideration the social evaluation provided by the community and **ii.** the COSMOS platform (central SA component) by gathering data from **a.** Followers directly or **b.** the COSMOS Registry.

For example, the second developed solution is a platform specific service that is initiated by the SA component and entails the querying of Followers of a specific VE. We refer to this VE as “Evaluated VE”. The first action of the SA is to acquire the Followers List of the Evaluated VE. The SA extracts the group of Followers of the EvaluatedVE and then randomly decides which ones and how many of them to use as a querying basis (if their number is too great). This element of randomness is essential in the development of the mechanism, as it can prevent collusions which may alter the final result of the evaluation process. After this step, the SA requests the stored Applauses and Shares (and Assists or Mentions if applicable) for the EvaluatedVE from the Followees List or Black Lists of each Follower of the VE. After receiving the requested metrics, the SA component calculates both the Trust and the Reputation Indexes which, combined with certain weights defined by the user, result to the Dependability Index. It should be noted that for the calculation of the Dependability, the EvaluatedVE itself does not provide any information at all, but instead, all the information needed is offered by its social environment.

6.2.2.3 Structural/Social Analysis Properties and Metrics

As we already discussed, the analysis and formalization of social relations among Things is critical and the computation of social measures is necessary. They improve the effectiveness of the system as they help in taking decisions at many levels. However, the analysis of social networks is basically related to their structural analysis. **Social Network Analysis (SNA)** is the analysis of social networks viewing social relationships in terms of network theory. These relationships are represented by nodes (individual actors within the network) and ties (relationships between the individuals). The computation of structural power is considered to be a step of high importance.

At a first level, it is important to refer to some Social Network Analysis properties and discuss the way they can help us identify the key nodes, the relationships strength (ties strength) and the cohesion of our social networks. There is a great variety of metrics that could be used under the functionalities of the Social Analysis, offering more detail and information about the networks being analyzed. The main metrics that have been identified and whose role is evident even at the early steps of the Social Analysis component are:

- **Centrality:** Centrality refers to a group of metrics that aim to quantify the importance or influence (in a variety of senses) of a particular VE or group of VEs within the network. Examples of common centrality metrics include degree centrality, closeness centrality, betweenness centrality, eigenvector centrality, alpha centrality etc [25]. Centrality is one of the main metrics that should be taken under consideration from the recommendation services.
- **Distance (Shortest Path):** The minimum number of ties required to connect two particular VEs, as popularized by Stanley Milgram's small world experiment and the theory of 'six degrees of separation'. This theory introduces the idea that each node in a freely emerged network can be reached by propagating items of information via six hops. Distance is important as it is involved in various other measures, e.g. closeness centrality and betweenness centrality. Closeness centrality is distance-based and increases when the distance between nodes decreases, while betweenness centrality is a measure of the number of shortest paths in a network that traverse the node.
- **Tie Multiplexity:** The number of content-forms contained in a tie of a dyad of VEs, in other words how many relationships represents a tie. For example, two VEs that can share knowledge will have a tie with multiplexity of 1, whereas, in case they can share IoT-services too, they will have a tie with multiplexity of 2 and so on. Multiplexity is associated with relationship strength and durability and may be an indicator of network effectiveness. Some other kinds of relationships that can be defined and affect the multiplexity of ties are presented in [20] and are the Parental object relationship, the Ownership object relationship, the Co-location object relationship etc.
- **Cohesion:** The degree to which VEs are connected directly to each other by cohesive bonds. Structural cohesion refers to the minimum number of members who, if removed from a group, would disconnect the group. This characteristic is quite important when reconfiguration of a group of VEs must take place.
- **Density:** The proportion of direct ties in a network relative to the maximum possible number of them. When density is close to 1, the network is dense and can resist to tie failures more easily, otherwise it is sparse. For density 1 the network is called a clique. Density is related to the speed with which information is diffused among the actors and is useful in comparing networks or different regions of a single network.
- **Centralization:** An aggregate metric that characterizes the amount to which the network is centered on one or a few important nodes.

- **Clustering coefficient:** A measure of the likelihood that two randomly selected neighbors of a node are connected to each other. It represents the density of a node's neighborhood. A higher clustering coefficient indicates a greater 'cliquishness' [26]. For an entire network it is computed as the average of all its nodes' clustering coefficients and represents the tendency to form clusters and groups.
- **Structural holes & Bridges (Mediators):** The structural hole concept, developed by sociologist Ronald Burt and sometimes called social capital [27], refers to the lack of ties between two parts of a network. The structural holes theory introduces the concept of bridges or mediators as individual actors that fill a structural hole, thus connecting two previously unconnected (or at least loosely coupled) actors and gain valuable insights in others work. Finding and exploiting a structural hole can offer novel and competitive innovation opportunities [28]. In our approach, mediators could be used to facilitate the communication between VEs and GVEs. Mediators can influence partners and build high reputation. Structural holes & Bridges can enable effective decentralized discovery mechanisms.

Other network level analysis metrics include average distance (average distance between all pairs of nodes), metrics that integrate attribute data with network data (for example, metrics that measure homophily) etc.

The structural metrics discussed above give us the opportunity to identify the key VEs in the network. The centrality metrics bring out the nodes of great 'importance'. For example, the degree centrality is a measure of a VE's connectedness and represents the number of friends it has in its neighborhood. The betweenness centrality (BC) is a measure of how often a VE is the most direct route between two other VEs and represents its potential to act as mediator. The closeness centrality (CC) represents how fast a VE reach every other in the network, whereas the eigenvector centrality (EC) represents how well a VE is connected to other well-connected VEs.

Of course, the importance of a VE depends on the context and use case. For example, in the home automation domain, high degree centrality may indicate the key room in a building, in the smart city domain, VEs of high betweenness that bridge various communities may be of great importance, while in the transport domain, VEs of high eigenvector that influence the whole network may be of greater significance (Table 1). The various metrics are correlated and they do not necessarily have the same tension. A VE with high eigenvector may not have high closeness and/or high betweenness, meaning that it does not have the greatest local influence and/or it has low bridgering potential.

Table 1: Types of Centrality and VEs' Roles.

Metrics	High BC	High CC	High EC
VE Roles	Mediator	Group Leader	Network Influencer

Reciprocity and multiplexity metrics bring out the tie strength. However, the aspects of heterogeneity, such as diversified bonds and/or dissimilar nodes, add more complexity. SNA could be enhanced by the use of tie weights (weighted network). Ties weighted in relation to frequency of interaction, influence, capacity etc. provide a more real world indication of the dynamics of a particular network. They affect the path that information takes, the speed it travels and may characterize the nodes that use them as more or less key ones. Thus, centrality measure results are affected by tie weightings. Moreover, centrality is affected by ties between

dissimilar VEs (multimodal network). A metric such as betweenness centrality applies to uni-modal networks and there is no clear definition in a multimodal one. All these mean that new algorithms are required for the calculation of centrality for weighted and multimodal networks.

At this point, it should be noted that, while some VEs relationships will be defined by the users, a great percentage of them will have to be appointed by the COSMOS platform. As a result, the case we study here is not just of an independent system from which some metrics are extracted for research, but instead a system where many times new relationships are appointed dynamically depending on known desired values of these metrics. In other words, instead of extracting the properties of an existing graph, we create a graph based on the desired values of the properties. Consequently, the creation and maintenance of the VEs' social environment is reduced to determining the proper metrics and their corresponding values.

In general, VEs' social networks will be self-organized, emergent and complex [29], such that globally coherent patterns will appear from the local interaction of the elements that make up the system. These patterns will become more apparent and rich as the size of the network increases. However, a global network analysis of all the relationships between millions or billions of VEs is not feasible and is likely to contain so much information as to be uninformative. The nuances of a local system may be lost in a large network analysis, hence the quality of information may be more important than its scale for understanding network properties. Thus, social networks should be analyzed at the proper scale, depending on the application or the needs of a user or a functional component of the platform. Generally, there are three scale-levels into which networks may fall: micro-level, meso-level and macro-level [30]. At the micro-level, social network research typically begins with tracing inter-VE interactions in a small group of a particular domain. Meso-level analysis begins with a population size that falls between the micro- and macro-levels and may also refer to analysis that is specifically designed to reveal connections between micro- and macro-levels. At last, macro level analysis generally traces the outcomes of interactions over a large population. It becomes quite evident that, in case we have to take decisions at system level regarding e.g. the reconfiguration of some entities, this kind of analysis becomes really important.

6.2.2.4 Computational Models and Social Network Tools

There are many tools that can be used from the Social Analysis component and a need for the development of new tools may exist. Some of the main tools that we have taken under consideration are:

- **Representation Formats, markup languages and ontologies:** DyNetML [31] and GraphML [32]] could be used as a reference model.
- **Dynamic Network Analysis and Social Network Analysis:** Tools for reasoning under varying levels of uncertainty about dynamic networks, their vulnerabilities and their ability to reconfigure themselves, choosing **Dynamic Network Analysis (DNA)** metrics and then using one or more of the available optimizers to find a design that more closely meets an ideal as well as exploring network graphs. The dynamic network visualization has been a challenging topic due to the complexity introduced by the extra dimension of time [33]. Some tools that have been studied are ORA, IGraph, Networkx and Pajek [34], [35].

The tool that has proven to be the most useful to us is **Gephi** [36]. Gephi is an open-source and free interactive visualization and exploration platform for all kinds of networks and complex systems, dynamic and hierarchical graphs. Its statistics and metrics framework offer the most common metrics for SNA and scale-free networks. Gephi is the ideal platform for DNA, since Dynamic structures, such as social networks can be filtered with the timeline component.

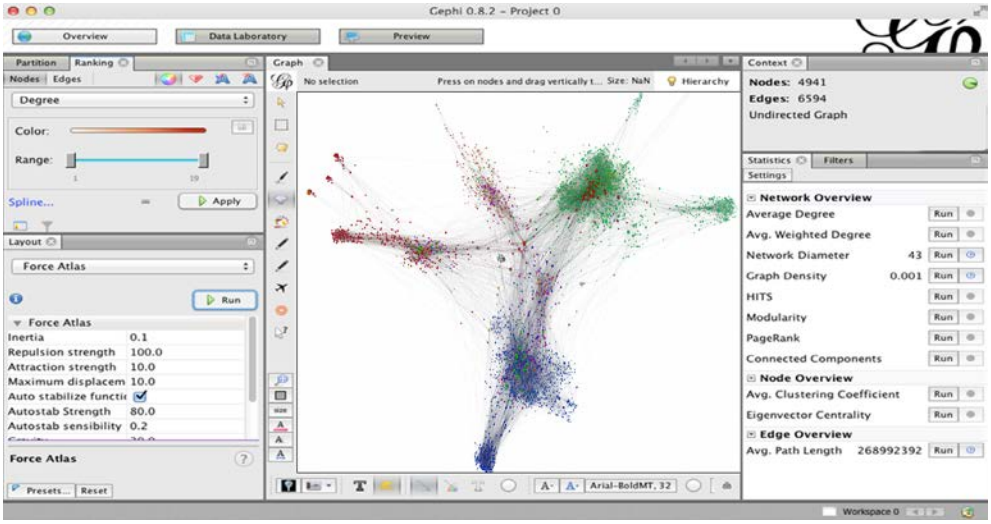


Figure 14: Network Analysis and Visualization using Gephi.

6.2.3. Social Contracts and Contacts Maintenance

When a Followee(s) recommendation request is sent to the platform and a new VE is chosen by the SA, the platform has to act as an intermediator to help the two VEs form a new bond and agree on a social contract. As such, the platform generates two passwords (a password and a countersign) and forwards them both with the corresponding VIP to the two VEs (the one asking for new Followees and the one recommended as one new Followee). The passwords do not have to be too complicated or even unique (Figure 12) since brute-force cannot be used against them as, once a wrong key is given during a request or a response to a request, the system/community gets informed. Through this mechanism, many security threats can be tackled. This concept is analyzed in D3.1.2 too. It should be noticed that these keys cannot be used at the opposite direction since the Follower-Followee relation is not symmetric. This means that in the case of two mutual Friends, four keys will be needed.

When the platform sends to the initial VE the VIP of the new Followee and to the new Followee the VIP of the initial VE, then the corresponding Followers and Followees lists are filled in. In order for a VE that changes its VIP dynamically to re-establish its bonds, it can forward its Friends Lists to the platform which will act yet again as an intermediator and re-establish the old connections by informing the Followers and Followees of the VE for this change. Of course, the platform has to make sure that the new VIP really belongs to the older VE (the platform can query the Friends presented in the lists; this information is only available to the original VE, unless it gets hacked).

A **decentralized approach** for the creation of social contracts can be used too. In this case, the intermediator helping two VEs to have their first contact will be another VE (probably a common Friend of theirs). The intermediator will create the two simple keys and forward them together with the corresponding VIPs to the two VEs. The two VEs, after their first contact, will agree on two new keys so that no other VE (even the intermediator) will be aware of them

While designing these mechanisms, the concept of **Opportunistic IoT** [37] should be taken under consideration. VEs (and their owners) should have some motives to agree on sharing their services with other entities of the network. A simple model would be to set a rule according to which a VE may access services of other VEs if and only if it provides some services of its own to the other VEs too. This leads to the idea that the social contracts could be used as a form of coin and the transactions between VEs could be "**monetized**" [38].

6.3. Trust & Reputation Management

6.3.1. Introduction

Trust and reputation (T&R) models have been recently proposed by many researches as an innovative solution for guaranteeing a minimum level of security between two entities of a distributed system that want to have a transaction or interaction. Thus, many studies, works and models have been designed, carried out and developed in this direction, leading to a current solid research field on which both academia and industry are focusing their attention. Many methods, technologies and mechanisms have been proposed in order to manage and model trust and reputation in systems such as P2P networks [39], ad-hoc ones [40], wireless sensor networks [40] or even multi-agent systems [42]. Such methods have been used in many environments like P2P networks, Wireless Sensor Networks (WSN), Vehicular Ad-hoc Networks (VANETs), Identity Management Systems, Collaborative Intrusion Detection Networks (CIDN), Cloud Computing Systems, Application Stores and of course the IoT.

T&R management is a very useful and powerful tool in environments where a lack of previous knowledge about the system can lead participants to undesired situations, specifically in virtual communities where users do not know each other at all or, at least, do not know everyone. It is in those cases where the application of trust and reputation mechanisms is more effective, helping a peer to find out which is the most trustworthy or reputable participant to have an interaction with, preventing thus the selection of a fraudulent or malicious one. Most of the current T&R models in the literature follow four general steps which are described by Marti and Garcia-Molina [43] (Figure 15):

1. **Collecting information** about a certain participant in the community by asking other users their opinions or recommendations about that peer.
2. **Aggregating all the received information** properly and somehow computing a score for every peer in the network.
3. **Selecting the most trustworthy or reputable entity** in the community providing a certain service and effectively having an interaction with it, assessing a posteriori the satisfaction of the user with the received service.
4. **Punishing or rewarding** according to the satisfaction obtained, adjusting consequently the global trust (or reputation) deposited in the selected service provider.

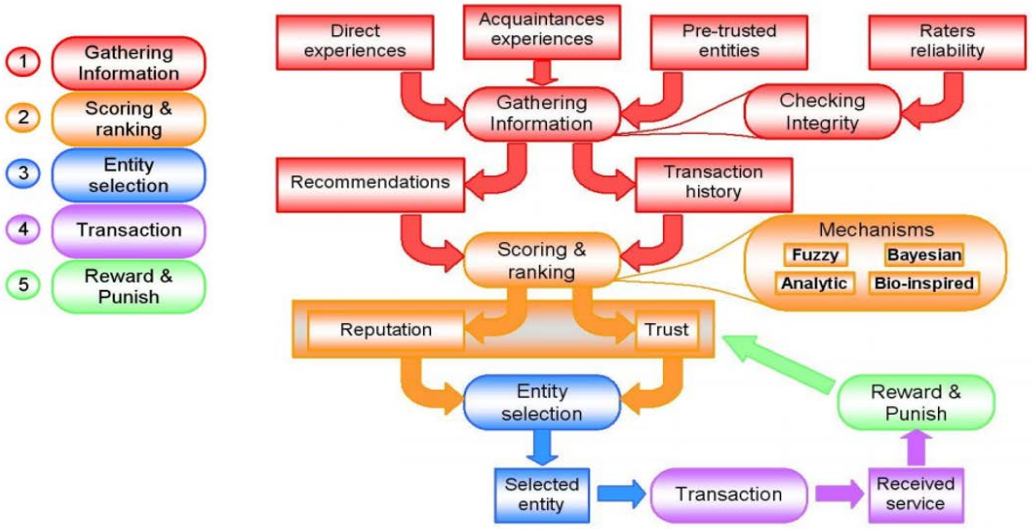


Figure 15: General steps followed in T&R models.

6.3.2. The COSMOS T&R model

Different models manage concepts such as Trust or Reputation in many different ways. For instance, some models like PTM [39], [44] or AFRAS [45] make use of fuzzy logic in order to deal with those topics, bayesian networks are used by MTrust [46] and BNBTM [47], bio-inspired algorithms are used in AntRep [48] and TACS [49], while other models like Eigentrust [50] or PeerTrust [51] just give some analytic expressions. Although there are some generic data structures for the domain of T&R provided for example by the Open Reputation Management Systems (ORMS) of OASIS [52], there are **no standards** for concepts like Trust and Reputation. In this subsection we try to provide some clear definitions of the main concepts that build up the COSMOS T&R model and the main features that characterize it.

6.3.2.1 Definitions

It is also worth mentioning that the distinction between a trust and a reputation model is not always clear. However, in our opinion, those models making an explicit use of other participants' recommendations could be categorized as reputation models while the rest could be considered just as trust models.

Let's assume that VE1 wants to find out some social characteristics of VE2 for a specific service offered. The following terms can then be defined:

Popularity (P): A counter which monitors how many times VE2 has received or may receive a request (how many "hits" it has). The Popularity Index is a property which indicates the total Shares and Mentions VE2 has. It is an accumulative and comparative indicator, and is used to determine the stability of Reputation and Trust.

Trust (T): The belief of VE1 that VE2 is going to deliver the correct service based on previous interactions of VE1 with VE2. The Trust Index of VE2 provided by VE1 is a property which states how many times VE2 has successfully shared its services with VE1 and it can be calculated as the ratio of the Applauses from VE1 to the Shares to VE1. Trust is subjective, because it is estimated from perspective of the individual trustor (VE1 in this case).

Reputation (R): The belief of VE1 that VE2 is going to deliver the correct service based on previous interactions of other VEs (in the social neighbor of VE1) with VE2. The Reputation Index can be calculated from the Trust that other VEs (apart from VE1) have on VE2. In other words, this metric determines the belief of others on a VE and is useful especially when VE1 does not enough data to extract a Trust Index for VE2 (because e.g. there are no interactions between the two VEs yet).

Reliability (R'): An absolute indicator of the performance of the VE that quantifies its efficiency to offer successfully its services relatively to its ideal or normal operation. The Reliability Index should be based on criteria like: response time upon request, ability to communicate (depending on how constrained is the VE or how constrained are the sensors/actuators associated with the VE), quality of provided etc.

Dependability (D): A social measure combining all the above social measures. It can be simply derived by the expression $\boldsymbol{D = a \cdot T + b \cdot R + c \cdot R' + d \cdot P}$ where a, b, c and d (non-negative integers) are the weights of the measures and $\boldsymbol{a + b + c + d = 1}$. For this calculation, Popularity has to get normalized. By selecting the appropriate weights, we can provide the expression of the Dependability Index that we want. For example, when there are only a few interactions between VE1 and VE2, then the Trust Index should have a low weight and the Reputation Index should have a high weight. This means that the weights should change dynamically and be set according to the users or developers preferences.

6.3.2.2 General Features

Reputation connects closely to the concept of Trust, but there is a clear difference, which can be illustrated by the following two scenarios:

- VE1 trusts VE2 because VE2 has a good Reputation. This reflects that Reputation can be used to build Trust.
- VE1 trusts VE2 despite the bad Reputation of VE2. This reflects that even if VE1 knows the Reputation of VE2, VE1 has its own private knowledge (e.g. direct experience about VE2) which is considered to be more important

Generally, a VE can be evaluated only by information gathered from other VEs. Its Dependability can be calculated by each and every other VE of the community (a subjective estimation) or by the platform (a more, but not totally, objective estimation). Depending on its (subjective or objective) Dependability and a threshold set by the user or the (VE or Application) developer, it can be chosen as a member of the Friends Lists or the Black Lists of other VEs. In case the VE is added to the Black List of another VE, a given amount of time has to pass for its redemption to take place.

Both big and small time-windows are used to quickly detect malicious or unsatisfactory behavior and avoid the fast redemption of blacklisted VEs. Moreover, feedback from recent interactions has a higher weight than this of older actions.

Benevolent VEs should have more **opportunities** than newcomers. As a result, newcomers with 0 interactions with other VEs will have Reputation equal to 0. However, an extra rule has to be applied to the model we have designed to give the opportunity to newcomers that have a low Reputation (because of the small number of interactions with other VEs) to be chosen as service providers at some point and start building their Reputation. For example, 10% of the recommendations from the platform should introduce newcomers to the rest of the community. The same applies for VEs which have low Reputation due to malicious or unsatisfactory behavior in the past. In other words, this rule enables the **social integration** and **reintegration** of the VEs to the system. Moreover, this rule is necessary for the first moments of the social community that will be born from COSMOS, as the network, at its **initial state**, will not have any VEs with high Reputation.

It should be noticed that, in contrast with many T&R models, we choose to use **different** Trust and Reputation **scores** for different services provided by the members of the network. This feature helps as face quite many security threats, described in subsection 6.3.4. For example, abuse of a high achieved Reputation is easily avoided.

From all the T&R models we have studied, the one that is the most similar to the model we propose is SORT [52], a self-organizing trust model for P2P systems.

6.3.3. Calculation of Trust & Reputation

6.3.3.1 The Trust Metric

Let's assume that VE1 wants to calculate the **Trust Index** of VE2 for a specific service offered. In order to do that, VE1 needs to maintain a log of its interactions with VE2. After each interaction VE1 stores to the log an evaluation of the service provided by VE2 through the Applauses metric. Applauses can take a value from 0 to 1 with a step of e.g. 0.5. Let's also assume that the behavior of the VE2 follows a normal distribution.

First of all, VE1 has to calculate the **average (μ)** of the interactions, by simply dividing the Applauses for VE2 with its Shares which are practically the **number of interactions (N)**. This is a measure of the overall behavior of the VE and it indicates the satisfaction level that VE1 will probably reach if it requests the service from VE2.

However, VE1 has to know how confident it can be about the value of μ, so it has to calculate the **standard deviation (σ)** of the interactions too. This measure shows how likely it is that VE2 will behave in a way that is close to μ.

To sum up, μ shows the satisfaction that VE1 should expect from VE2, while σ shows how predictable the behavior of VE2 is. **Trust (T)** is calculated as:

$$\boldsymbol{T = \mu - \sigma}$$

This means that if that T = 0.5 then there is an 84% probability that the satisfaction for the service will be 0.5 or greater.

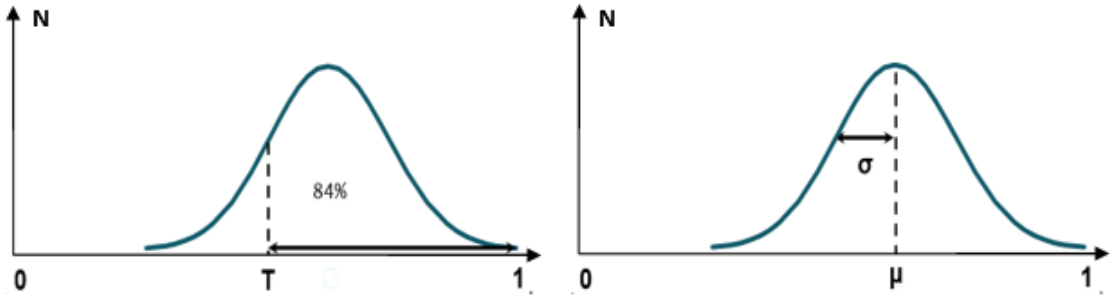


Figure 16: Calculation of the Trust Index of a VE.

We should take into account that the **Importance** of older interactions should decrease as new interactions take place, so that VE2 will not be able to misbehave by relying on its good history. The **weights** of all interactions are assigned their max value at the time the interactions take place and, after every new interaction is completed, all the weights from of the interactions are lowered by e.g. 5% (of the initial value of the weight which is 1). If the weight of an interaction gets lower than e.g. 0.1, then it is not taken under consideration for the calculations. There is also a timer that lowers the weights even when no new interactions are taking place.

Another important issue regarding the calculation of Trust is the **time-window** we use. Every time Trust has to be calculated twice, once for the full log **(T_L)** and once for e.g. the 1/10th of it **(T_S)**. The final value of Trust is:

$$\boldsymbol{T = min(T_L, T_S)}$$

This is approach is adopted in order to quickly detect any (probably malicious) **behavioral change**. If VE1 has a small number of interactions with VE2, then T_S can be calculated by the full log and T_L can be assigned the Reputation value of VE2 (see next subsection).

6.3.3.2 The Reputation Metric

When VE1 wants to request a service from VE2 for the very first time, it has to rely on the experience of its social circle since it cannot calculate any Trust value. This means that VE1 asks some of its Followees (those that are used for recommendation services for a specific service) how much they trust VE2 and calculates the **Reputation Index**.

In the beginning, VE1 requests from its Followees with a high Trust value for recommendation services ($\mathbf{T_{rec}}$) the number of their interactions (N) with VE2 and the corresponding Trust value (T). These Followees are depicted with green in Figure 17. If only a few Followees return these measures, then VE1 lowers the threshold of T_{rec}. After receiving a sufficient amount of answers, VE1 calculates the **initial Reputation Distribution**. This is done by calculating the **weighted average** and **weighted standard deviation** where the weight used for each Followee is calculated by the values of N and $\mathbf{T_{rec}}$ coming from it.

After this first step, VE1 requests from all (or, if too many, from a sufficient number of) the remaining Followees-Recommenders their N and T value for VE2. These Followees are depicted with blue in Figure 17. If the values provided by a Recommender are within the **range [μ_r-0.7σ_r , μ_r+0.7σ_r]** which is the range that VE2 is expected to behave 51% of the time, then the recommendation is considered correct and is used to modify the distribution. Else it is considered malicious and is ignored. If the recommendation is considered correct, the T_{rec} of the Recommender is increased by e.g. 1-10%, else it is decreased. In the end of this procedure, the feedback of the highly trusted VEs is evaluated too. It should be noted that if there is no trusted Recommender, VE1 will ask the platform for a centralized calculation of the Reputation of VE2.

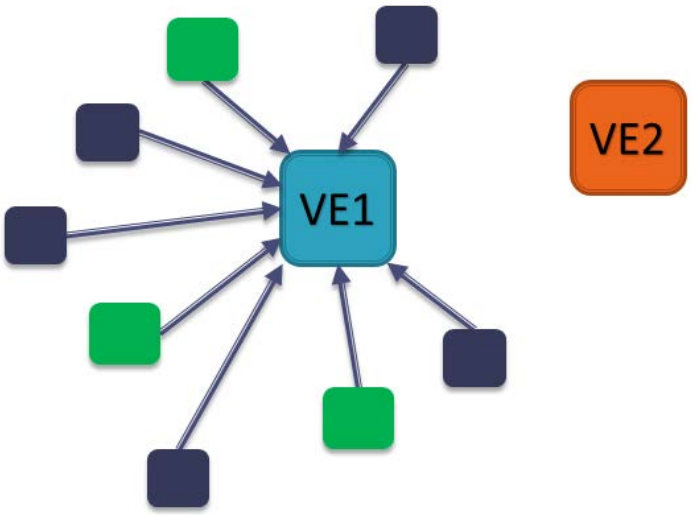


Figure 17: Collecting information from the social circle to calculate Reputation.

To sum up, Reputation is calculated by taking into account the Trust that other VEs have for VE2 and the trustworthiness of these VEs regarding their recommendation services. The final value of Reputation is:

$$\boldsymbol{R = \mu_r - \sigma_r}$$

It should be noticed that with this approach, we can calculate both the Reputation of a VE and the Trust for other VEs that act as Recommenders. The importance of this characteristic of our model can be better understood in subsection 6.3.4 where we analyze the several threats that our T&R model will have to face.

6.3.4. Security Threats Scenarios

Trust and reputation management over distributed and heterogeneous systems has emerged in the last few years as a novel and accurate way of dealing with some security risks related to these environments. Thus, many models and theories have been developed in order to manage T&R in those communities effectively and accurately. Nevertheless, very few of them take into consideration all the possible security threats that can compromise the system and most models involve the arising of new threats that should not be underestimated.

In [54] Marmol and Perez, in order to provide a reference guide for developing secure trust and reputation models, present and describe the most common security threats applicable in the field of T&R management over distributed environments. Every accurate and T&R model should have some mechanisms to effectively overcome all the threats that could be applied to it. After studying several T&R models like EigenTrust [50], PeerTrust [51] and PowerTrust [55], we realized that not all the models address all the possible threats and, in fact, some of them do not even deal with these risks at all. In our opinion, this is an issue that should not be underestimated when designing and developing a new T&R model over distributed and heterogeneous systems, since an inaccurate management of these threats could result in important security deficiencies and weaknesses.

In the next subsections, we analyze the main security threats that can be applied in our T&R scheme. Moreover, we develop a complete taxonomy of these threats by describing several possible dimensions of attacks over our T&R system and categorizing them according to these properties. Finally, we discuss the solutions that our model offers for overcoming these threats and will suggest possible extra ways of tackling each one of these risks in the design phase.

The model we provide can be tested through simulations. Experimental results will be necessary in the future to find out how it reacts against certain attacks.

It should be stressed out that these kinds of security threats are strongly linked to the T&R model we design. Therefore, their analysis must be done within the “jurisdiction” of WP5 and not this of WP3 which focuses on hardware security, cloud storage security and the concept of Privelets. Of course, there are some cases that discussions between the two WPs become necessary. One representative example is the threat of Sibyl attacks which will be described in the next sub-section.

For the analysis that follows, we consider scenarios where several participants (entities, nodes, peers) belong to a virtual community where a certain set of services is offered. When a specific participant is requested to provide one of the services it offers it can either provide the offered service with a good quality and act in a benevolent way or provide the offered service with a bad quality and act fraudulently or maliciously.

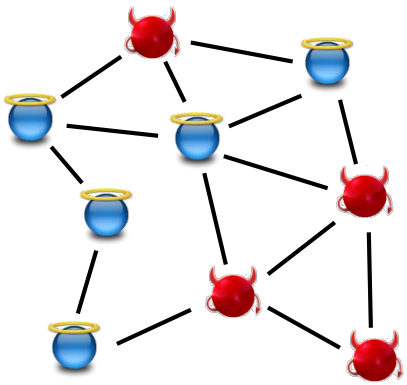
Special attention should be given to the fact that not all the bad services are a product of maliciousness, but may also result from wrong applications logic or malfunctions. For example, when a VE shares “wrong” cases, this does not mean necessarily that it is a malicious VE, since these cases may have been produced while sensors of the VE were malfunctioning. However, this detail does not affect the analysis we present later.

Finally, we also make a distinction between the recommendation services and the rest of the services provided by the VEs. When a VE provides recommendation services, it will be considered to be a **Recommender**, while, when it provides any other kind of services, it will be considered to be a **Service Provider**.

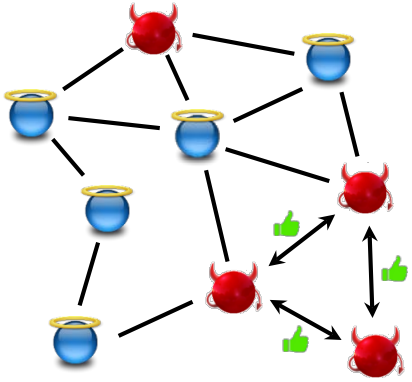
6.3.4.1 Description of Security Threats Scenarios

The main threats that have been identified are:

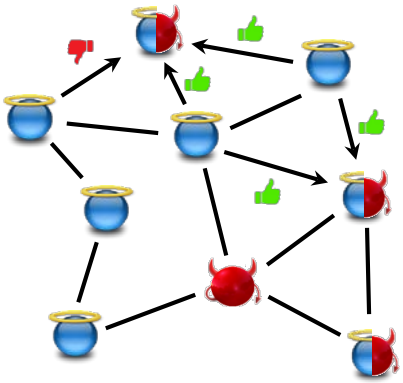
a) **Individual malicious VEs:** A malicious VE always provides false services and information when selected as a service provider or a recommender. This is the simplest threat that can be found in a trust and reputation system (Figure 18a).
b) **Malicious collectives of VEs:** Malicious VEs that provide bad services collude to unfairly provide high ratings about each other. That way the platform or individual VEs of the network can be manipulated to believe that the collective is trustworthy. Not many trust and reputation models treat the problem arisen from the constitution of a collusion among malicious peers, having thus an important security deficiency (Figure 18b).
c) **Malicious VEs with camouflage:** When malicious VEs are selected as service providers or recommenders, they provide bad services and recommendations in p% of all requests. This is, in many cases, a threat which is not always easy to tackle, since its resilience will mostly depend on the behavioral pattern followed by malicious peers. For instance, it is not the same battling against an oscillating pattern (being fully benevolent for a period of time, fully fraudulent for the next period and so on) with battling against an increasing and decreasing one or even a random one (Figure 18c).
d) **Partially malicious VEs:** A partially malicious VE for certain services it behaves properly while for other specific services it acts maliciously. For example, a VE could increase its reputation by providing good services to many requests of minor importance while it would provide bad services to a few important requests. In such a situation some distortion can emerge, considering a peer as fully or quite benevolent although it can also provide some fraudulent services (Figure 18d).
e) **Malicious Spies:** Malicious spies always provide good services when selected as service providers, but they also give the maximum rating values to malicious nodes too. In this threat, the malicious spies may gain a high level of trust and reputation, since they always provide good services. Then they may be able then to easily subvert the trust and reputation mechanism applied in the system (Figure 18e).
f) **Sybil Attack:** In this case, an attacker may initiate a disproportionate number of malicious VEs in the network. Each time one of these VEs is selected as a service provider or recommender, it provides a bad service and, after its reputation gets low, it is disconnected and replaced with a new peer identity [56] (Figure 18f).
g) **Slanderers:** Malicious VEs that provide bad services collude to unfairly provide high ratings about each other, but also to provide low ratings about benevolent VEs. In such a situation, if an interaction has never been performed with a VE which is actually benevolent but whose reputation has been driven down by malicious participants, then that VE will not probably be chosen as the one to have an interaction with (Figure 18g).
h) **Man in the middle attack:** In this case, a malicious VE intercepts the messages from a benevolent service provider VE to the requestor and replaces them with bad services, making therefore the reputation of the benevolent VE to decrease. This is a great threat especially when the COSMOS decentralized discovery mechanisms are used, like in the case of XP-sharing with TTL>1 (Figure 18h).
i) **Malicious pre-trusted VEs:** Pre-trusted VEs that provide positive recommendations about malicious nodes and negative ones about benevolent nodes (Figure 18i).



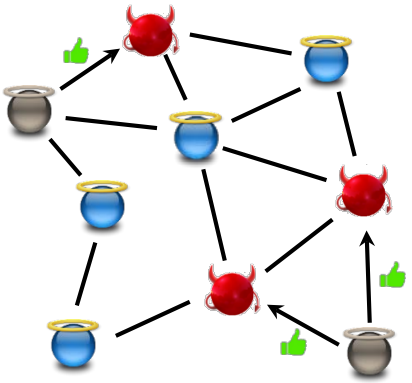
a. Individual malicious VEs.



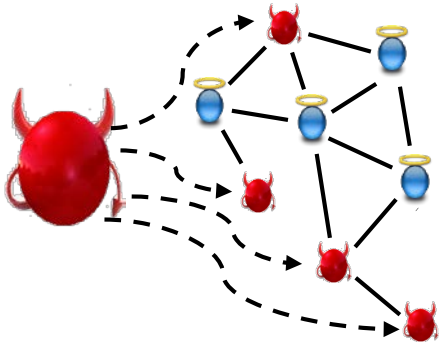
b. Malicious collectives of VEs.



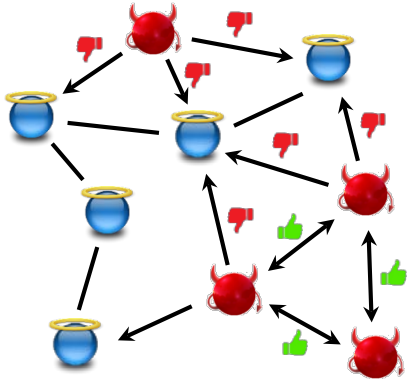
c. /d. Malicious VEs with camouflage and partially malicious VEs.



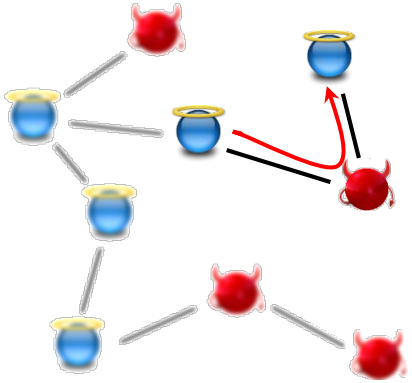
e. Malicious Spies.



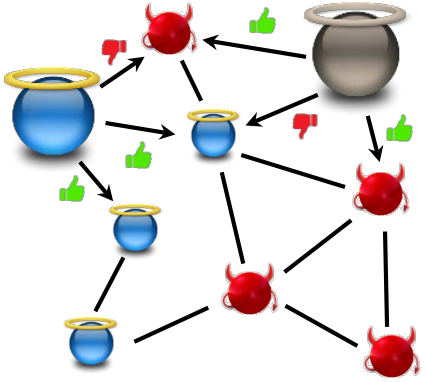
f. Sibyl Attack.



g. Slanderers.



h. Man in the middle attack.



i. Malicious pre-trusted VEs.

Figure 18: Security threats in the COSMOS T&R model.

6.3.4.2 Security Threats Taxonomy

After identifying the several threats that our T&R model has to face, it is useful to categorize them according to some properties that will help as evaluate them more efficiently. For this reason, we are going to adopt some ideas presented in [57] regarding the analysis of a generic security threat for T&R systems. So, dimensions of the threats that should be taken under consideration are:

- **Attack intent:** While the direct result of attacks is generally that the evaluations made by the T&R system are manipulated in some way, there are three straightforward intents behind them: **i.** fraudulently praising entities in order to increase their reputation in the system, **ii.** driving down the reputation of reliable entities and **iii.** damaging the reputation system as a whole, so that users will decrease their trust in it and, eventually, stop using it. For instance, malicious collectives and malicious spies attacks will try to unfairly praise and increase the reputation of some entities which actually do not deserve it.
- **Targets:** Security threats may focus their efforts on: **i.** specific individual entities belonging to the system, **ii.** subsets of entities and **iii.** the whole community (making no distinctions). For example, individual malicious VEs and man in the middle attacks can be classified as individual attacks. It is in an attacker's best interest to limit the effect of an attack to a small target set of entities in order to be more subtle and try to avoid detection by the system.
- **Required knowledge:** Attacks may require some level of knowledge about the items, users, ratings and algorithms in the T&R system being attacked. Some threats require a comprehensive knowledge about the whole system or about some particular entities, while some other threats work properly with a small knowledge about it (its users, the T&R model applied, ratings distribution etc.). For example, creating a collusion will need more information about the system (each member of the collusion needs to know the rest of them) than an individual attack such as the individual malicious VE attacks. Generally, further knowledge about the system can help in choosing which attack to employ and in tuning attack parameters to maximize effectiveness and minimize detectability.
- **Cost:** The less expensive an attack is, the more beneficial is its application. Once again, the cost of running an attack is not necessarily economic, but it can be also measured in terms of resources or time requirements. Thus, some threats will have a higher associated cost and will be therefore more difficult to be performed, while others will be easily applicable, since their corresponding cost will make them worthy. In most cases, the cost of applying an attack is directly related to its associated amount of required knowledge. The only case where both dimensions do not match is for the Sybil attack, because although it needs (nearly) no knowledge about the system, it is not usually so easy to create a disproportionate number of entities enough to cause a really important damage to the community. The following factors contribute to the cost of a given attack: **i.** size of attack, **ii.** difficulty of interacting with the recommender system, **iii.** difficulty of obtaining required knowledge about the algorithm, users, entities and ratings in the recommendation system, **iv.** any other resources required for attack planning or execution, such as additional logistical, computational, or technical requirements.
- **Algorithm dependence:** Some attacks may be specifically designed to exploit a particular weakness in a specific algorithm or class of algorithms, while others might be more general and can be effective against a variety of algorithms. More specific attacks will intuitively require fewer resources for the same effectiveness, but require detailed knowledge of the algorithm being used and its parameter settings. For example, malicious pre-trusted peers, is a specific threat related and, therefore, only applicable to those T&R algorithms or models which actually make use of pre-trusted peers.

- **Detectability:** Finally, an attack over T&R systems is desired to be as less detectable as possible. The later an attack is detected, the higher might be the damage it will cause. That is the reason why most of the threats act trying not to induce suspicion as much as possible, (i.e. they do not cause drastic changes in the system but they rather make slight ones). In some way, the detectability of an attack or threat is a measurement of its resilience and effectiveness. Thus, the easiest threat of the previously presented ones to be detected would be the individual malicious VEs. As the collaboration between attackers and their gathered knowledge about the system increases, those attacks become more and more undetectable. That is the reason why all the threats based on a collusion are, generally, more difficult to tackle.

Based on the available literature, we can make an estimation about the several properties of the attacks that our T&R system will have to face. This is depicted in the following table:

Table 2: Security threats and their corresponding properties.

Security Threats	Properties of the Attacks					
	Intent	Target	Required Knowledge	Cost	Algorithm Dependence	Detectability
Individual malicious VEs	(iii) Damage	Individuals	Low	Low	Generic	High
Malicious collectives	(i) Praise	Subsets	Medium	Medium	Generic	Medium
VEs with camouflage	(iii) Damage	Individuals	Medium	Medium	Generic	Low
Partially malicious VEs	(iii) Damage	Individuals	High	Medium	Generic	Low
Malicious Spies	(i) Praise	Subsets	High	High	Generic	Low
Sybil Attack	(iii) Damage	System	Low	High	Generic	Low
Slanderers	(ii) Slander	System	High	High	Generic	Low
Man in the middle attack	(ii) Slander	Individuals	Medium	Medium	Generic	Medium
Malicious pre-trusted VEs	(iii) Damage	System	High	High	Specific	Low

6.3.4.3 Solutions for overcoming Security Threats

a) **Individual malicious VEs:** The way of preventing such a misbehavior is by decreasing the level of trust or reputation of those participants who always provide bad services, categorizing them, therefore, as malicious VEs. The model we provide faces this simple problem successfully.

b) **Malicious collectives of VEs:** The most crucial step in overcoming this threat is making a distinction between the trust indexes used for the evaluation of the VEs when they act as recommenders and the trust indexes used for the evaluation of the same VEs when they act as service providers. Many T&R models do not make this distinction. However, as it is discussed in the previous sections, COSMOS does make this distinction, thus this threat can be faced satisfactorily, since the malicious collectives will be regarded as bad service providers and recommenders from the benevolent VEs.

c) **Malicious VEs with camouflage:** From their nature, these VEs have to provide sometimes good services, since their total number of bad service transactions is bounded by p%. Thus, these VEs will not necessarily cause heavy damage, especially in the case where the trust standards (thresholds of the acceptable trust indexes) set by the other VEs are high, ensuring a high p%. Indicatively, the variable behavior of these VEs is not even considered as a threat

in many T&R models in the sense that they do not punish that kind of behavior, but they just try to adjust the trust and reputation given to a peer to its real and current goodness. Other models, however, demonstrate the uselessness for malicious peers to behave in this way. It should be noted that, in the case of COSMOS, Trust incorporates the standard deviation of the behavior of the VEs, ensuring that their bad behavior will be limited even more. Finally, the variable behavior of a peer, when detected, could be punished and avoided. However, to achieve this, storing a part of the transactions history becomes necessary.

d) **Partially malicious VEs:** There are some trust and reputation models which are not resilient to this kind of attack since they just perform a global computation of the trust and/or reputation of a peer, regardless the service they are providing. On the other hand, COSMOS, by just considering a different score for every service offered by a VE (e.g. different Friend Lists for different Applications), can mitigate this threat most of the times. However, it should be tested whether this distinction is always practical, since in some environments (for instance, those with a great amount of services offered) it could lead to some scalability problems. Finally, different weights could be added for the evaluation of different services depending on their importance.

e) **Malicious Spies:** Like in previous threats, an accurate management of the reliability of the peers, not only as service providers, but also as recommendation providers may effectively help to prevent this kind of abuse. This is the case for COSMOS, so Malicious Spies will be used as service providers but not as recommenders.

f) **Sybil Attack:** Yet again, not many T&R models deal with such an important and potentially dangerous threat, thus leading to an underestimated but great risk. A reputation system's vulnerability to a Sybil attack depends on how cheaply Sybils can be generated, the degree to which the reputation system accepts input from entities that do not have a chain of trust linking them to a trusted entity and whether the reputation system treats all entities identically. One of the most common solutions proposed in the literature for this kind of threat consists of associating a cost to the generation of new identities in the community. This cost is not necessarily economic, but it can also be a cost in terms of time or resources for instance. Another suggested way of dealing with this problem [60] makes use of a central entity managing (virtual) identities in the system or even a set of identity providers ensuring that every participant in the community has a unique and immutable identity.

g) **Slanderers:** The differentiated management of the trust given to a participant when supplying services and the reliability of its recommendations can be very useful in this scenario as well. Moreover, in the case of COSMOS, the platform or even some benevolent VEs have a 10% chance of recommending a random VE below the reputation thresholds. That means that no matter how low the reputation of a benevolent VE becomes because of slanderers, it will eventually be recommended to new benevolent VEs which, after their first interactions, will give it a high trust rating and ignore its bad reputation in the future (if it remains bad after the new connections).

h) **Man in the middle attack:** One more time, this is a threat which has not been associated with T&R systems traditionally. Most of the models consider or assume the authenticity of the VE providing either a service or a recommendation. Nevertheless, as explained before, this attack can cause a great damage in the system if its application is possible. A solution proposed in the literature is the use of cryptography schemes in order to authenticate each user in the system. However, it is not always feasible to apply such a solution, above all in highly distributed environments like those we are trying to build. **COSMOS introduces a new solution, by using the concept of Assists described earlier, an interaction metric that is used for the evaluation of VEs as Mediators**. In our case, only the direct Friends of a VE are evaluated, meaning that only direct service providers or mediators are evaluated by the VEs. This means that a man in the middle attack would result in the low rating only of the

malicious VE (which would gather many negative assists) thus helping the benevolent VE to remove this Friend from its Friend List, and maintaining the good reputation of the VE whose services where changed by the mediator.

i) **Malicious pre-trusted VEs:** It is worth mentioning that it is not always feasible to find a set of peers that can be trusted before any transaction is carried out in the system. Some models base their strategy on this kind of participants. However, and maybe in a paranoic way of thinking, every user in a virtual community can behave inappropriately at some point. If such a thing occurred with a pre-trusted peer, the system would be at a risk. For this reason, we have decided not to use pre-trusted VEs in the COSMOS system, since their existence does not seem necessary for now.

6.3.5. Evaluating and Testing our T&R model

It is not always easy to check the correctness and accuracy of a model and even more to compare it against other trust and reputation models. In order to test our T&R model, we are going to use one of the best simulators for T&R models we came across, the **TRMSim-WSN** [61]. The TRMSim-WSN is a Java-based T&R models simulator aiming to provide an easy way to test a trust and/or reputation model over WSNs and to compare it against other models. It allows the user to carry out customized simulations by adjusting several parameters such as the percentage of malicious nodes or the possibility of nodes forming collusions. Moreover, it offers an API which provides a template for the users to help them easily load new T&R models to the simulator [62]. Finally, it is possible to load to the simulator new networks from a XML file.

By loading to the simulator our own T&R model and the networks extracted from the COSMOS Use Cases, we will be able to run many tests before the actual deployment of the corresponding components. That way, we will be able to determine whether the security threats described above are faced successfully and our model covers the main goals we have set regarding the T&R management of VEs.

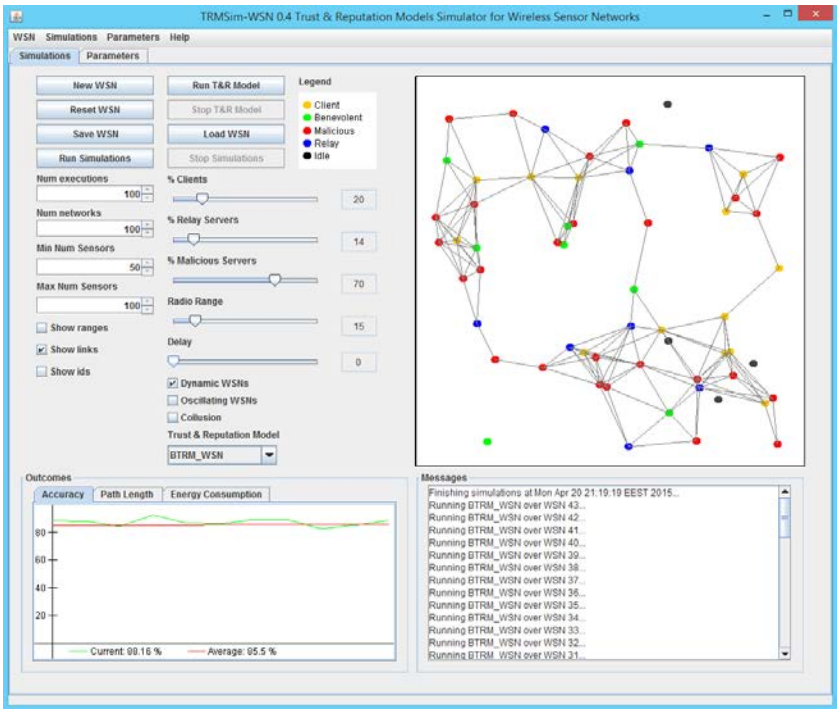


Figure 19: TRMSim-WSN, Trust and Reputation Models Simulator for WSNs.

6.4. Relational Models

Till now, the concept of Friendship between VEs has been discussed in detail. However, taking under consideration the SIoT paradigm introduced in [20], we can realize that other kinds of relationships between VEs can be defined too. The information that these relationships can provide when extracted may provide more options for the development of new mechanisms. A representative example is the Replacement Relationship that we are going to introduce.

Ownership Relationship: The Ownership Relationship is a simple relationship which is established between objects that share the same owner. It is primarily a **user based** relationship. This means that the users play an important role in the formation of these kinds of relationships. The rare change of the owner of a VE makes the relationship a **static** one. This means that Ownership Relationships are not subject to frequent changes and have a longer duration than other types of relationships. This duration also makes the relationship more **"reliable"** than others, as there is less room for errors during its detection. The Ownership Relationship is a **symmetric** one, meaning that if a VE1 has an ownership relationship with another VE2, then the same applies for VE2. The main property that is needed to establish an ownership relationship between VEs is the **Owner ID**, an identification that matches to the user that owns a VE. Extracting the relationship is fairly trivial. If two VEs share the same Owner ID, then they form an Ownership Relationship. The motivation behind extracting this relationship lies in the need of knowledge flow between VEs that share the same owner. Through interaction with the owner and with the use of sensors, VEs may be able to acquire information that could prove useful to the other VEs owned by the same user.

Common-User Relationship: The Common-User Relationship is similar to the Ownership Relationship, with a notable difference in the types of users that take part in its creation. This relationship is established between VEs that share a common simple user. A simple user of a VE is defined as the user who has partial access to the VE regarding its use, maintenance and permissions. Simple users can have various levels of access to the referred VE, however the extent of this access is decided only by the owner who has full control of the VE. A typical example of a simple user is a person who rents a car (VE-car). The Common-User Relationship is primarily a user based relationship. The frequent change of active users of VEs makes the relationship a more **dynamic** one. However, this relationship is more reliable than others, as there is less room for errors during its extraction. The Common-User Relationship is a **symmetric** one. The main property that is needed to establish such a relationship between two VEs is the **Simple Users List**, a list containing all the User IDs of simple users that are actively using a VE. Yet again, extracting the relationship is fairly trivial. If two VEs share a simple user, then they form a Common-User Relationship. However, providing a framework where a Users List is created is not an easy task, so actual real detection of this relationship may not be one of the features that we will provide. The motivation behind this relationship is the same with the one for the Ownership Relationship. As an example, let's assume that George who lives in Greece and drives an IoT-enabled vehicle, equipped with sensors gathering information regarding his driving habits, has at some point to travel to Italy for a business trip. When he visits Italy, he rents a car which is IoT-enabled as well. By establishing a Common-User Relationship, the two VE-cars may share any information available regarding the driving habits of George.

Follower/Followee Relationship: The followers/followees relationship may be either **VE based** or **Application based**. This means that the VEs themselves and Applications play an important role in the formation of these kinds of relationships as it has already been analyzed. The ephemeral nature of friendships makes this relationship a more dynamic one. The followers/followees relationship is an asymmetric relationship.

Parental Relationship: The Parental Relationship is the relationship that is established between VEs and their higher ranked counterparts. A higher ranked VE is defined as the VE that has permission to monitor and control, to some extent, VEs that are configured to be under its authority. The parental relationship is VE and Application based. Authorities are decided per application and are not that often subject to change, something that makes the relationship a more static one. The parental relationship is also a strictly asymmetric one. This relationship is closely related to the concept of GVEs that COSMOS introduces. The motivation behind this relationship is the introduction of the element of authority between VEs (per application) which is necessary to some extent to all communities aiming for autonomy. The existence of a VE with a more central role, able to organize and control the group can help prevent decision deadlocks and solve conflicts when and if they appear.

Co-Work Relationship: The Co-Work Relationship connects VEs that work on the same Application. Applications may need groups of VEs to form teams in order to share resources like specific knowledge or IoT-services. The importance of Applications in this relationship makes the Co-Work Relationship an Application based one. The type of an Application plays an important role in the nature of this relationship. Applications can be of fixed size, with a predefined number of VEs involved, or of an evolving size, with VEs joining and leaving the Application constantly. The duration of Applications can vary as well. Applications can have a predetermined duration or may be of "open time". All the above characteristics make the Co-Work Relationship a dynamic relationship and of variable reliability, depending on the Application characteristics. For example, a fixed size and fixed time Application will form more reliable Co-Work Relationships than an evolving in size, "open time" Application. The Co-Work Relationship is a symmetric one.

Conflict of Interest Relationship: The Conflict of Interest Relationship is established between VEs that may enter into conflict with each other. Conflicts are created when VEs vie for the same resources, either in the form of critical information or in the form of vital (IoT-)services that can be offered to a limited number of VEs. The importance of Applications in this relationship makes the Conflict of Interest Relationship an Application based one. This means that Applications define the formation of these kinds of relationships between VEs, by providing necessary information for their detection. The main information that has to be examined to extract this kind of relationship is the List of VEs aiming for a common resource and an Importance Table (e.g. a VE from the domain of e-Health will have greater priority than one from the domain of Home-Automation). The table is necessary for determining any kind of priority between VEs in order to ultimately resolve the conflicts.

Replacement Relationship: The Replacement Relationship is a relationship that can be established between a VE (VE1) and another VE (VE2) which has the capacity to replace the first one. This means that, for a specific Application and type of service, VE2 can be used in an identical way as the VE1 that is replaced. The Replacement Relationship is an Application based relationship. A challenge that all Application based relationships share is the consequences of VEs participating in more than one Applications at the same time. The amount of possible Replacement Relationships for all Applications is too high to ensure a scalable network. Therefore, to overcome this, this relationship will always be established for one particular Application and the corresponding service at a time. The replacement of VEs may have various levels of success. When multiple VEs are able to act as replacements, the most efficient and successful one must be chosen first. In order to achieve this, a **Replacement Rating** is introduced, a rating system that measures the replacement efficiency of a VE. Once a replacement is completed, VEs can rate their replacements based on their level of success. This level can be measured as the percentage of completed tasks during the replacement period. The motivation behind the Replacement Relationship is to ensure the smooth operation of Applications. The solution we propose is as follows. A VE that offers its services to some

Applications could maintain a Replacements List which would contain the addresses of other VEs that offer similar services in similar conditions and cover specific needs of the Applications. In case one of the services of the VE becomes unavailable, then the corresponding VE is informed. The main concepts and mechanisms used for the Follower/Followee Relationship can be applied here too.

Co-Location Relationship: The Co-Location Relationship is a relationship that is established between VEs that are close to each other. Proximity of VEs is defined as the distance between the two corresponding Physical Entities that satisfies a given lower threshold. This relationship can be used for example in Applications for weather forecasting or geological and geographical surveying. The Co-Location Relationship is a **Location** and **Application based** relationship. Calculation of location is a complex procedure which requires different levels of accuracy, depending on the scope and scale of the Application. The main property that needs to be examined is the **Geolocation** of the VEs, especially the **hasGeoLat** and **hasGeoLon** data-type properties. However, as mentioned before, the necessary threshold to determine proximity needs to be set by the Application. For that purpose, the **GeoBoundaries** property of the Application could be introduced. GeoBoundaries is a set of coordinates that create a geographical boundary, determining the area and therefore the threshold on distance for the VEs to be considered close to each other. The motivation behind the Co-Location Relationship lies in the plethora of location based information that can be gathered by a VE and may be deemed useful for other VEs as well.

Table 3: Types of Relationships and their dimensions.

Relationship	Ontology Focus	Type	Reliability	Direction	User Properties	VE properties	Application Properties
Ownership	User based	Static	High	Symmetric	Owner ID	-	-
Common-User	User based	Dynamic	High	Symmetric	User ID	Simple Users List	-
Follower/ Followee	VE/App based	Dynamic	-	Asymmetric	-	Subsection 6.2	Subsection 6.2
Parental	VE/App based	Static	High	Asymmetric	-	-	List of VEs GVE members
Co - Work	App based	Dynamic	Varying	Symmetric	-	-	List of VEs
Conflict of Interest	App based	Dynamic	Varying	Symmetric	-	Domain	List of VEs Importance Table
Replacement	App based	Dynamic	Varying	Asymmetric	-	Services Rating	List of VEs
Co - Location	Location/ App based	Dynamic	Low	Symmetric	-	Geolocation	GeoBoundaries List of VEs

7. Network Runtime Adaptability

7.1. Participants in Network Runtime Adaptability scenario

COSMOS aims at enabling the customization of services offered to final users and automatizing (at least at some extent) the improvement of various parameters describing the performance of the network. In this context, the network refers to all the entities and systems that participate in the scenario of runtime adaptability. The next figure highlights them.

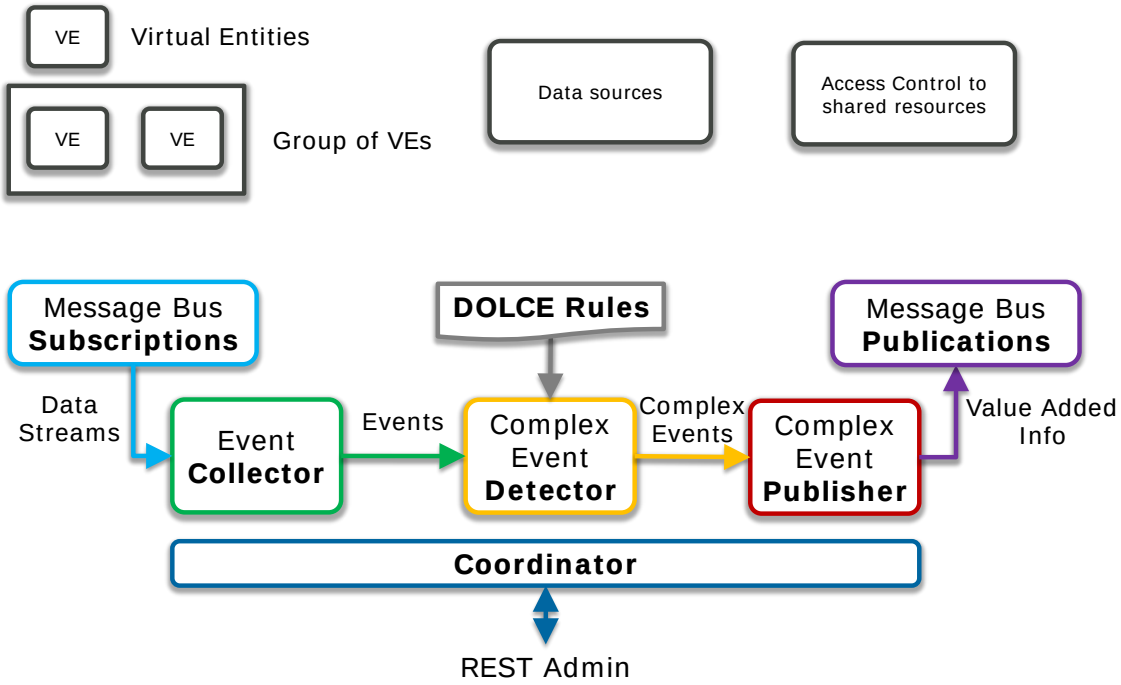


Figure 20: Components participating in the Network Runtime Adaptability scenario.

There are several components and entities that can play an important role in the optimization of the overall system performance by adapting to various situations:

- **Virtual Entities** are linked to Physical Entities. Their reconfiguration has as an implication changes in their parameters such as the costs related to their functional mode, their power consumption, the data provision and data processing. When a group of VEs can be affected by the same optimization, a GVE is addressed by the Network Runtime Adaptability mechanisms.
- **Data sources** are not limited to VEs providing the information they collect but extend to other elements (mainly open data platforms) that can provide extremely useful information for the development of a service. Nevertheless, sometimes the services could collect data in many different ways. The different ways that data can be collected represent another challenge that can be addressed by the Network Runtime Adaptability mechanisms.
- **Access Control** to shared resources. Access to the information provided by all the components defined in COSMOS can be dynamically modified based on several rules. For example, emergency situations or cases where specific areas of the system are under maintenance may lead to failures. These circumstances should be detected and the system should be alerted.

- The **CEP engine** plays a very important role in the mechanism we introduce and adaptation actions can be applied to each one of its modules.
  - **Event Collector:** The Event Collector is in charge of generating the events that the detector will evaluate based on the rules compiled in the CEP engine. Changes to the events in runtime can provide to the whole system an adaption capability that can increase its performance.
  - **Complex Event Detector:** The role of the detector does not vary. However, it should be mentioned that DOLCE rules can be updated in runtime via the coordinator module.
  - **Complex Event Publisher:** This module connects the outputted complex events of the CEP engine (that can modify the behavior of any of the aforementioned modules) to the Message Bus, assuring their delivery.
- The Message Bus is not an entity whose functionalities will be adapted under the Network Runtime Adaptability paradigm. However, it is a key module that guarantees the delivery of the messages to their destinations.

In the following subsections we analyze how all these entities and components can get adapted.

7.2. Network Runtime Adaptability with COSMOS components

In the COSMOS SotA deliverable, the project has described the different levels of Situational Awareness as well as the Context Information classifications that are available. The one that has been chosen and the rationale for its selection can be followed in D6.1.2. In summary, Situational Awareness is composed by:

- the **perception** level – get information from data sources
- the **understanding** level – process data received and react if needed
- the **predicting** level – compose received data with previous processed data and explore them looking for patterns that can be derived from/for predictions.

Regarding the context information, the classification selected is the so called general classification, which basically divides context information in four categories:

- **System context:** It corresponds, for a given Application, to the context information of the system (software and hardware) on which the Application runs as well as the contextual information of the used communication system (for example, the wireless network type).
- **User context:** It can be any information that can characterize a user. This may be his/her age, location, medical history, biometric information, emotions, activities, social relationships etc.
- **Environment context:** It represents information that describes the physical environment and is not covered by the system or user context (particularly the context information from external sources such as temperature).
- **Time context:** It represents all the information related to time (hour, day, month, year, …).

All these terms represent the conceptual components that enable the Network Runtime Adaptability. In this sense, the awareness level defines the actions that can be applied in the COSMOS system. The next figure summarizes how all these concepts are related to each other and what kind of decisions can be extracted from the evolution in the processing and analysis of the information.

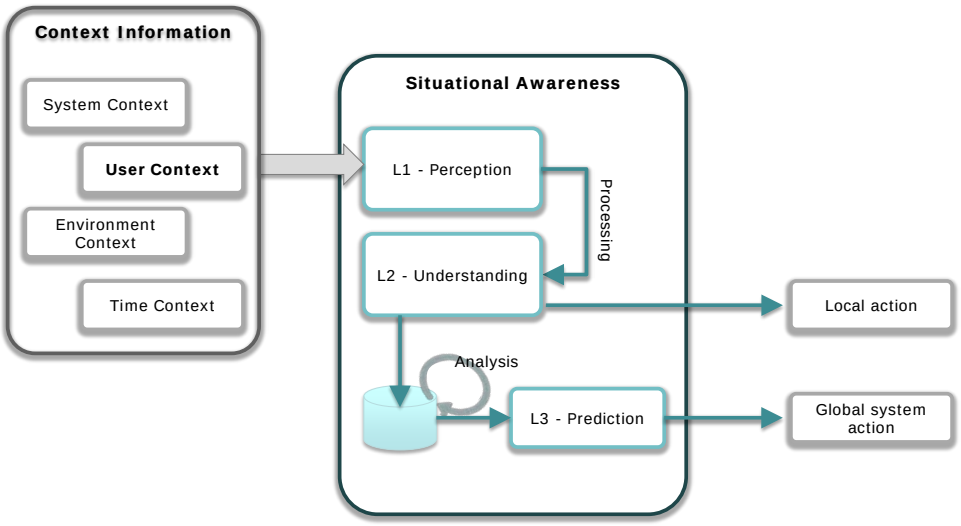


Figure 21: Flow towards Runtime Adaptability.

Taking as reference this diagram, it is easy to understand how the different levels of data processing can be transferred into actions that imply modifications of the behavior of components. In the next subsections, we provide a detailed analysis of the actions that can be performed and of the flow that the system will follow, from the time of detection until the time of execution of the needed updates/adaptations.

7.3. CEP actuation in network runtime adaptability

The µCEP engine is a key element for the scenario of runtime adaptability. As it has been presented in D4.1.2, the engine can be implemented in a centralized way (all the modules running in the same machine) or in a distributed way (different machines running different instances of each module). In the worst case, what this structure allows is the application of local actions derived from the execution of rules in the Complex Event Detector module.

Initially, it is necessary to map all the actors in their positions inside our scenario. In order to do so, the next figure establishes where they are and the concepts they are linked with.

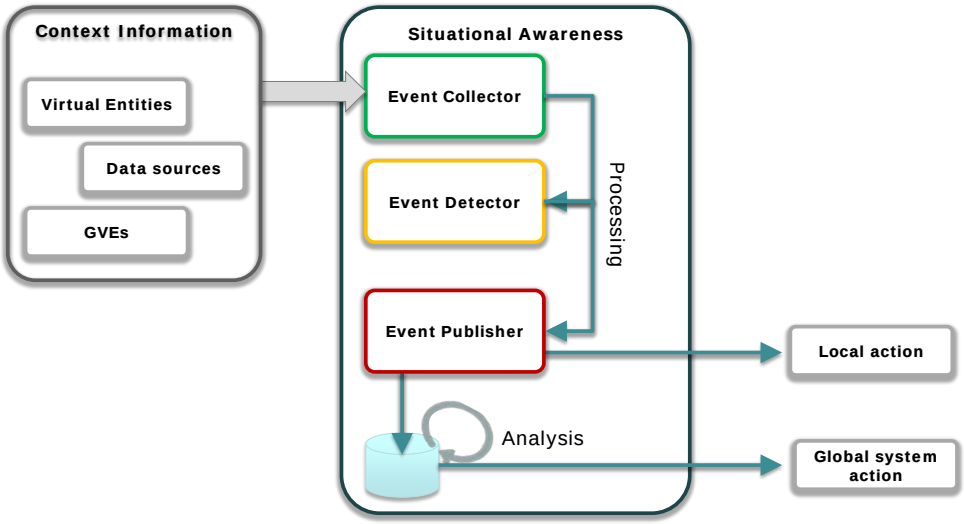


Figure 22: Concept mapping over real components.

The flow makes sure that data sources are processed at several levels, depending on the processing done, the data nature and the volume of data. The corresponding decisions taken have different impacts. The picture considers a generic implementation of µCEP. It should be noticed that we take under consideration the simplicity of the devices that will take part in the future IoT paradigm. Thus, the implementation is designed to fit in low power, constrained devices, opening new possibilities to automatize the advanced management of them.

In order to move from the conceptual world closer to reality, it is mandatory to establish the link between the actions and actuations and the real objects and machines that will implement them. The next figure presents the wide picture of how COSMOS concepts would be implemented in the most general scenario.

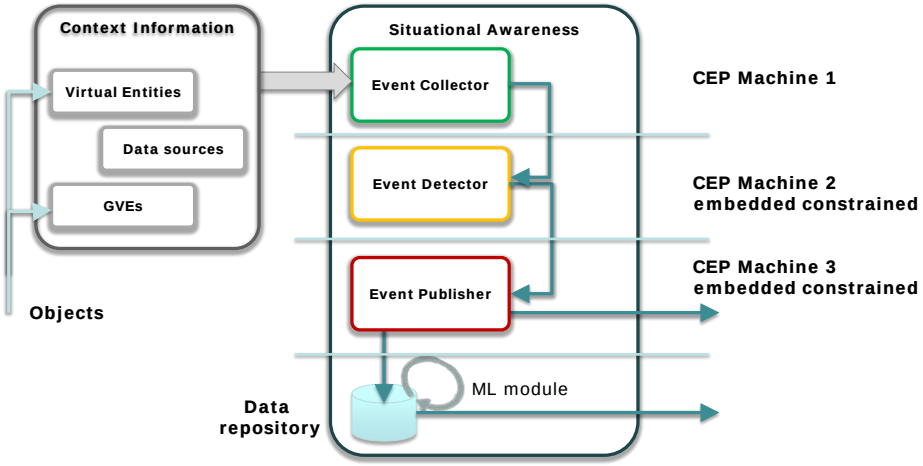


Figure 23: Mapping over real implementation.

Now that it has been explained how the different components fit in the COSMOS architecture, we can analyze the different actions that can be performed and the ways they can be shared in order to notify all the involved parties properly.

7.4. Decisions taken in Network Runtime Adaptability

In previous sections, the different elements that can be customized by the Network Runtime Adaptability mechanism are presented. For the sake of clarity, in the next figure the Machine Learning module has not been included even though it is co-working with the Complex Event Publisher module for distributing and triggering actions using the Message Bus.

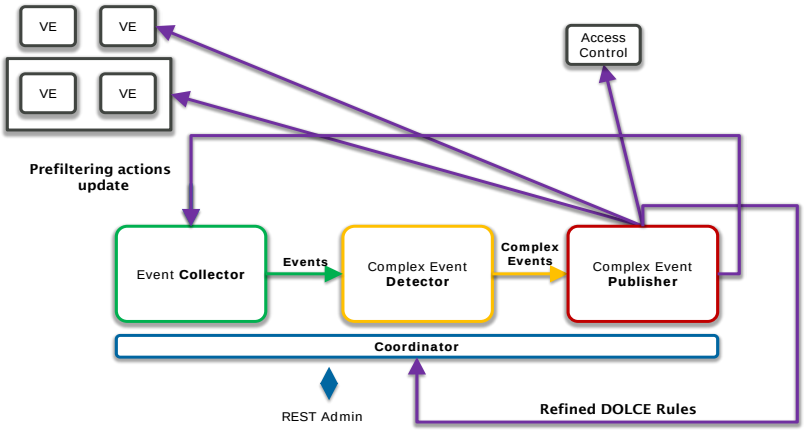


Figure 24: Decision distribution in Network Runtime Adaptability.

The decisions that have been defined are the following:

- Refinement of DOLCE rules in µCEP
- Refinement of pre-filtering actions and event generation
- Dynamic update of access control rules for sharing resources
- Modification of the behavior of VEs
- Modification of the group behavior of GVEs

The first three actions are related to the modification of the way that information is analyzed or accessed, whereas the last two actions focus on the optimization of functional processes related to the Physical Entities and the VEs.

Table 4: List of events that modify in runtime components' functionalities.

Action	Type	Destination	Impact
Refinement of DOLCE rules	New event detection	Complex Event Detector	Run time modification of the rules that applies to certain events. This also means adding new rules as long as the systems evolves.
Refinement of pre-filtering	New event generation	Event Collector	The Event Collector module could require to add more data sources in order to identify the new events that can be defined by DOLCE rules.
Modification of VE behavior	Change of individual entity behavior	VE – Object	A VE can have multiple functionalities from sensing to actuations over physical systems. In this sense, the modification of certain parameters may have a strong impact on the Physical Entities' performance, thus it is really important to have the capability of remotely managing this aspect.
Modification of GVEs behavior	Group modification	Several VEs – Object(s)	^The same rationale is applied to GVEs.

7.5. CEP adaptability implementation

The implementation of the Complex Event Processor provides a REST interface to manage the files containing Dolce programs. As any change in a dolce program affects the programmatic structure of the Event Detector module, any changes performed in a dolce program will have as a result a soft restart of Event Detector to rebuild the structure of the detector engine. In a Dolce program there will be three types of declarations or statements defined by three reserved words:

- **External:** to declare variables that can be modified in runtime.
- **Event:** to declare incoming events.
- **Complex:** to declare the rule defining a complex event.

As a REST interface uses JSON format in the body it is possible to change many parameters that define the way the CEP operates. The following table summarizes the methods available.

Table 5: Methods for the adaptation of the CEP.

Method	Description
Get DOLCE Rules files	Gets the list of DOLCE Rules files being processed in a CEP instance
Get a DOLCE Rules file	Gets the DOLCE Rules file details by the given name
Add or Modify a DOLCE Rules file	Add a new DOLCE Rules file or modify an existing one by the given name
Delete a DOLCE Rules file	Delete the DOLCE Rules file by the given name
Get the External declarations	Get all external declarations in a DOLCE program
Add/Modify an external declaration into a DOLCE Rules file	Add a new event declaration or modify an existing one into a DOLCE Rules file
Delete an external declaration into a DOLCE Rules file	Delete an event declaration into a DOLCE Rules file by the given name
Get the Event declarations	Ges all event declarations in a DOLCE program
Add/Modify an event declaration into a DOLCE Rules file	Add a new event declaration or modify an existing one into a DOLCE Rules file
Get the Complex declarations	Get all complex declarations in a DOLCE program
Add/Modify a Complex declaration into a DOLCE Rules file	Add a new complex declaration or modify an existing one into a DOLCE Rules file
Delete an event declaration into a DOLCE Rules file	Delete an event declaration into a DOLCE Rules file by the given name
Delete a Complex declaration into a DOLCE Rules file	Delete a Complex declaration into a DOLCE Rules file by the given name

By using of these methods, the adoption of the runtime modifications done over the components running a CEP becomes possible.

7.6. Hierarchical update of IoT devices

One of the most promising aspects of the Network Runtime Adaptability is the ability of VEs to dynamically modify the firmware they are running. In this sense, the management will be done by defining a hierarchy of devices and events. Additionally, the distributed implementation of µCEP will facilitate the continuous optimization of this scenario by simplifying the management procedure of the VEs.

The actions presented before may have as a result the partial or complete reconfiguration of VEs. This hierarchical update aims to exploit a two level cognitive system. First of all, the VEs with a µCEP engine are able to make their own decision improving their performance. However, the view they have is limited as they are not aware of the full picture and, consequently, higher level entities that can access this information are needed. Secondly, following this approach, it is also possible to ensure the proper behavior of a VE regardless of its connectivity to other entities and higher layers. A set of hierarchical actions will be derived and applied where needed.

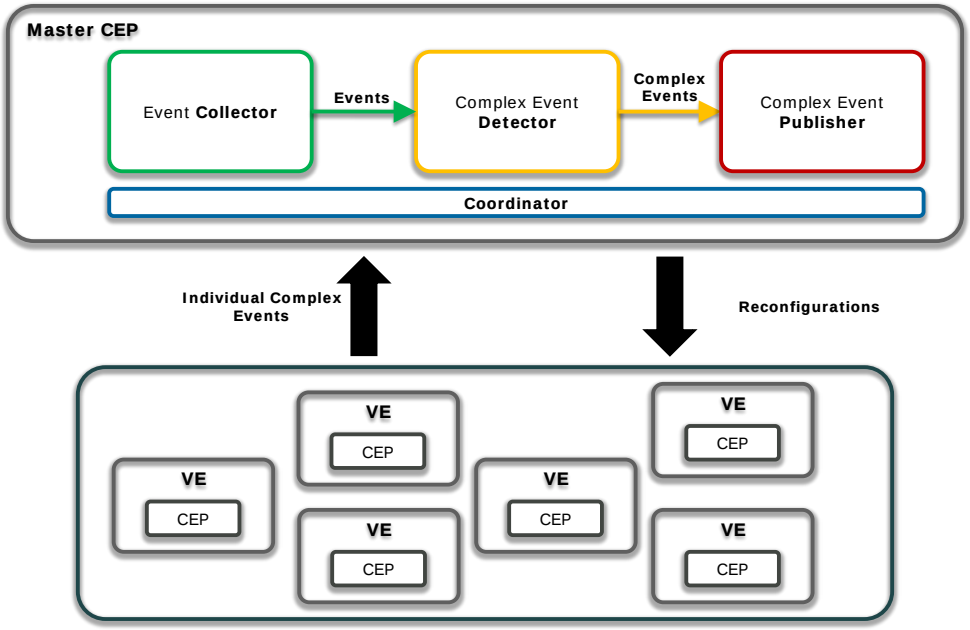


Figure 25: Hierarchical architecture of adaptability.

The modification of functional parameters or even of whole functionalities of a VE in real life offers a huge number of opportunities. However, there are several threats that must be minimized. The two level approach assures that compromising the security of one VE –for example, injecting a malicious software version– will not have a huge impact into the others. Once the rules injected in a sandboxed-µCEP are securely set and stored, the individual modification by malicious software of VE just affects these specific individual components.

In the IoT world there are several mechanisms for performing the remote update of devices [62] and also for doing it in a secure, efficient and reliable way [64]]. However, in all cases the update is triggered by end users, so this proposal goes a step beyond by adding autonomy to the system. The combination of efficient distribution with an effective decision making engine will have to be explored. It goes without saying that the usage of components described in the previous sections (e.g. the Planner) is in our initial plans.

8. Management Components

In this deliverable we decided to focus on the analytic description of functionalities, models and mechanisms we developed and will develop instead of focusing on the description of functional components. This was mainly done because most of the components developed by WP5 were already described in D5.1.1 but the mechanisms linking them were not presented in detail. However, in this section we provide a short description of all our functional components, addressing their core functionalities and relating them to the previous sections. All of the components are depicted in Figure 26. We do not analyze the components introduced in section 7 since they are described in detail.

Planner: The Planner of a VE is its brain, the component that enables it to reason on its Knowledge Base and take decisions depending on its situation. This functional component enables the VEs to use CBR, giving them the ability to learn from their own experiences and the experiences of other VEs. The Planner can be used for adaptation, but also for prediction too, depending on the way it is used. The Planner reasons on Cases defined by the Applications, but also on Cases for the self-management defined by the COSMOS platform (System Cases), enabling VEs to make reconfigurations and change some of their critical parameters. Finally, the Planner can be used generally as an Ontologies Comparator. This characteristic of the Planner combined with the functionality of the Decentralized Discovery component enables the evaluation of various COSMOS entities and the introduction of recommendation services. The functionalities of the Planner are analyzed in section 2.

Decentralized Discovery component: This component is closely related to the XP-sharing functional component described in the deliverables of WP6. By using RESTful interfaces, individual VEs are connected on a peer to peer basis and can communicate with each other by sending and answering to requests for discovery of several entities. This component works closely with the Planner and uses the lists maintained by the Friends Management component. In Section 3 the mechanisms on which this component is based are described in detail.

Social Monitoring (SM) component: This component contains all the main tools and techniques that are used for the monitoring of the social interactions of the VEs (e.g. Shares, Applauses) and of the social properties of the VEs (e.g. Trust and Reputation). Its main objective is to collect, aggregate and distribute monitoring data (events) across the decision-making components of the collaborating groups. The events are generated by interactions in response to - directly or indirectly - user actions (e.g. registering a new VE) or VEs' actions (XP-sharing). Social Monitoring forwards its results to the Friend Lists of the VE and can "feed" the Registry with these data on demand or periodically. Social Monitoring is analyzed mainly in subsection 6.1.

The Social Analysis (SA) component: Based on the results of the Social Monitoring component and taking advantage of Social Network Analysis (SNA) [65], the SA component is used for the extraction of complex social characteristics of the VEs (e.g. centrality), as well as models and patterns regarding the behavior of the VEs and the relations between them. The services and functionalities of the Social Analysis component will be used by both the users (External use) and other functional components (Internal use). From the plethora of the metrics available and the social interactions that can be monitored, it is quite evident that the Social Analysis component can provide a great number of functionalities, depending on the needs of the system. Briefly, the functionalities that have already been presented in this deliverable are: computation of the Dependability Index of VEs, recommendation of VEs, extraction of structural characteristics of the networks, extraction of relational-models and finally, modelling and visualization of networks. These functionalities are analyzed in subsections 6.2, 6.3 and 6.4.

Friends Management (FM) component: This component is responsible for creating and maintaining all the Friends Lists and Black Lists that a VE has. In other words, it allows VEs to initiate, update and terminate their friendship with other VEs on the basis of the owner's or developer's control settings. It provides the owner with the option of setting new Friends to his/her VEs, offers friend-recommendation request services and monitors the Friend List of a VE regularly or on demand in order to find any Friends whose Dependability is no more the desired one and thus should be removed. For this purpose, the FM component communicates with the SA component. Features of this component are presented in subsection 6.1.

Profiling and Policy Management (PPM) component: This component is responsible for assigning a unique ID to the VE and enables the entry of all the information needed for the description of the physical entity through the domain ontology of the corresponding VE. Moreover, it enables the owner to determine the social "openness" of the VE: the IoT-services that can be used by other VEs, the kind of experience that can be shared, the sets of VEs which can access such information etc. However, the "openness" of VEs is affected by the social selfishness, a basic attribute of human beings. Thus, while designing this component, the concept of Opportunistic IoT [37] should be taken under consideration. Moreover, preferences regarding the thresholds, taken under consideration when social interactions take place (e.g. the Dependability thresholds), could be received through this component.

Registry: The role of the Registry is to provide the adequate functionality for the retrieval of VEs and other COSMOS related entities descriptions. This Registry is in fact a semantic Registry and is backed by the core COSMOS ontology. The Registry and the corresponding ontologies are described in sections 4 and 5.

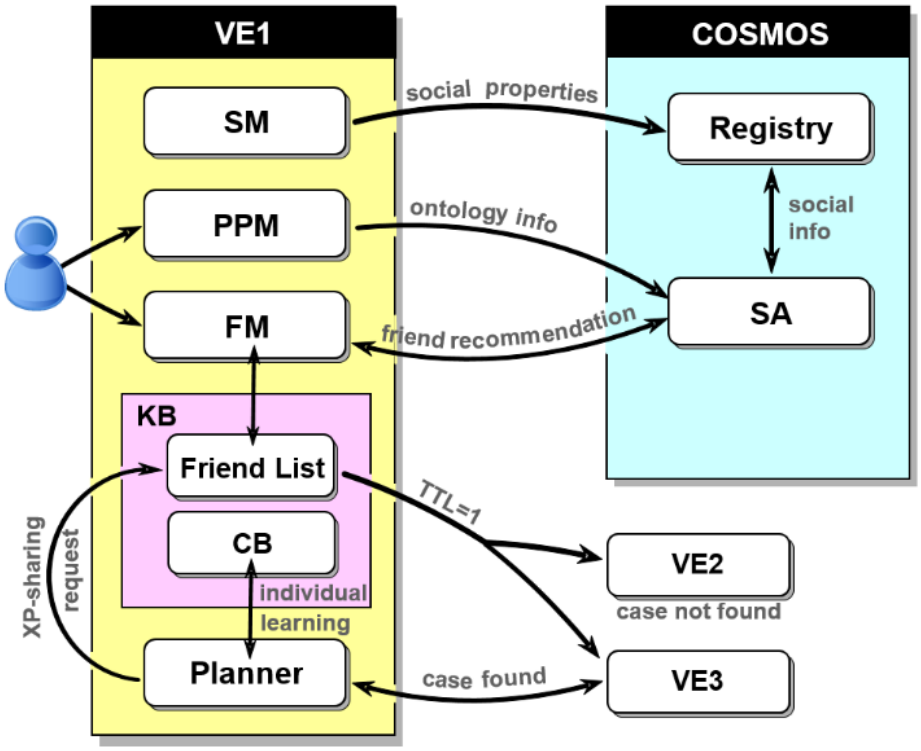


Figure 26: Conceptual view of WP5 components.

9. Show-casing our framework through an App

In this section we show-case our framework through analyzing the several steps needed to design a COSMOS-enabled Application. To do that, we adopt one of the Application Use Cases described in D7.1.2 (subsection 4.6) which is focusing on minimizing demand for heat energy production in smart-flats.

The **actors** that are taking part in this scenario are the:

- **VE Developer:** The VE developer is responsible for building COSMOS compliant VE-flats. He/she is responsible for respecting the APIs needed to register a VE with the platform and make it accessible to other VEs though well-known interfaces.
- **Application Developer:** The Application developer provides the (COSMOS-enabled) Applications utilizing the COSMOS offerings or mixing it with input from the VEs.
- **COSMOS Platform Provider:** COSMOS platform provides services through a standard interface to applications and VEs.
- **End-User (user):** The end-user is the entity that uses the COSMOS-enabled applications. The end-user runs the application which may use preconfigured VEs or VEs discovered at run-time.

The scenario described in D7.1.2 is as follows:

- Taking under consideration his/her **budget**, the owner of a flat (user) wants to set a **heating schedule** for his/her flat.
- To assist him, the IoT platform EnergyHive [66] designed by Hildebrand will use meters to report **real-time energy consumption information** automatically and remotely.
- Depending on these data, the user will change his/her consumption accordingly, thus reducing (sometimes) his/her **energy demand** (cost) and, as a result, minimising **carbon production**.
- This scenario however has as a **postcondition** that the user can optimise his/her schedule. With COSMOS this condition is not needed. Moreover, COSMOS may be able to offer a **prediction** regarding the total budget needed for a schedule.

The scenario as it is now implies the monitoring of the readings of smart-meters by the End User and the need for continuous modification of settings of the program. Such an approach is time consuming and will eventually alienate users even if the data are provided in understandable monetary terms and not in consumption metrics. Taking under consideration the services that are offered by COSMOS, we can provide an improved scenario. According to it:

- Taking under consideration his/her **budget**, a user wants to set a **heating schedule** for his/her flat.
- The user plans a **program**, stating which is the **desired temperature** value for his/her flat for **specific time intervals** of the day/week etc.
- Because of COSMOS, the flat has a **knowledge base** of past programs that can be used and thus it is able to estimate **a)** how the actuators should be used to achieve the best possible consumption (not necessarily the optimal one) and **b)** the needed budget.
- Even if the flat does not have a good program in its knowledge base, it will be able to ask other similar flats for help.
- The user does not have to act in an optimal way but just states his/her desires. Moreover, a prediction regarding the total budget needed for a schedule is provided by COSMOS from the very beginning.

The main Physical Entity is the user's flat. Each flat should be equipped with:

- A **temperature sensor** measuring the temperature **inside** the flat.
- A **temperature sensor** measuring the temperature **outside** the flat. This is optional, as this information may be available by a weather website for example.
- The EnergyHive system providing real-time readings for the **energy consumption** (energy "**sensor**").
- A **valve up/down control system** (**actuator**).
- A device used for setting the schedule and (for example) displaying the readings of the sensors, e.g a **tablet ("interface")**.

The Virtual Entity (VE-flat) that will act as the virtual counterpart of the Physical Entity to the cyber-world will:

- expose the services of the Physical Entity (sensors/actuators) through **IoT-services**, using REST endpoints.
- be equipped with **functional components** provided by COSMOS like the Planner and the XP-sharing component.
- have a **Knowledge Base** consisting of:
  - a **Case Base** where cases are stored and retrieved or changed by the Planner and
  - one **Friends List** (for each application) with the addresses of other similar VEs used by the XP-sharing component.
- be linked to the **COSMOS platform** (using platform functional components). **Applications** will be using capabilities of the VE.

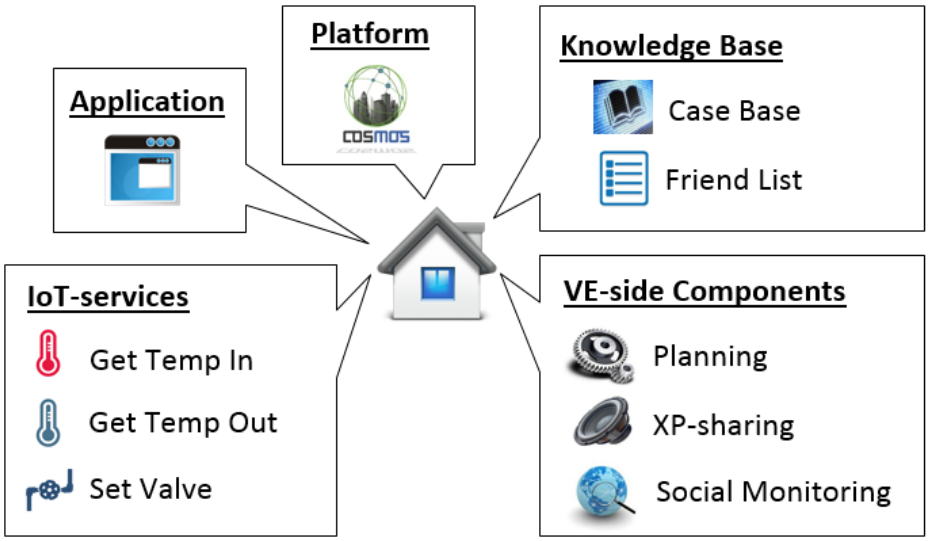


Figure 27: The COSMOS VE-flat.

The VE developer will have to:

- create the **IoT-services** of the VE.
- provide the **semantic description** of the Physical Entity and the services (VE and IoT-services) – Domain Ontology provided.
- **register** the VE to the COSMOS platform – COSMOS Ontology added.
- download the appropriate COSMOS "**system-code**" (Planner etc.) to the device where the VE "runs". In our case, this device could be a gateway or the tablet of the flat.

Regarding the Domain Ontology, properties of the flat needed in our scenario are:

- **location:** This property is needed for finding the right external temperature from data provided by weather-websites.
- **total surface** and **total volume (space):** may be needed for calculating the optimal (theoretical) energy consumption of the flat for a given schedule.
- **U-value:** An 'overall heat transfer co-efficient' which measures how well parts of a building transfer heat. U-values form the basis of any energy or carbon reduction standard.

These properties are also used as a **selection criteria for Friends**. The **Application developer** has to state which these criteria are and what their weights are.

Based on the Application logic, a CBR cycle will be formed:

- As it is mentioned in subsection 2.3.1, the CBR cycle has four steps: Retrieve, Reuse, Revise, Retain.
- The user wants a schedule for his/her heating needs. He/She inputs **a)** the **desired temperature** for **b)** a **period of time** (e.g. 1 day) and **c)** his/her **budget**.
- The application **creates** one or more new **Problems** based on this input.
- The Planner searches in the Case Base for Cases with similar Problems and returns the **Solution**. If nothing is found, XP-sharing is initiated (Retrieve).
- The user accepts the Solution or not (Reuse) and later he/she may provide feedback (Revise/Retain).

Regarding the **Problem Creation** defined by the Application logic, the inputs needed are **a)** the **desired temperature** for **b) periods of time** (e.g. throughout 1 day) **c)** for a given maximum **budget**. (When the user is away from home, we may not care about the temperature.) For every e.g. **half-hour** of the time-periods of interest, we create a **Problem** with properties:

- **Initial temperature inside** (provided by the corresponding IoT-service, needed only for the first problem)
- **Desired (final) temperature inside** (given by the user)
- **Temperature outside** (predicted by a weather website)

Thus, we create a chronological series of Problems. If we find Cases with similar Problems, we can use their Solutions.

Now, regarding the Solution Retrieval defined by the Application logic:

- A solution has as properties the **URI** of the IoT-service for setting (or not doing so) the valve and the **energy consumption** that corresponds to the problem.
- By executing the URIs at the corresponding time intervals, the **heating schedule** is executed.
- From the sum of the energy consumption of each individual Solution, we can find the **total (predicted) energy consumption**. This has to be lower than the **maximum energy consumption** defined by the user's budget. This can be calculated by the budget and the cost of kWh provided by a website.
- If we want to evaluate the Solution, we can also find the **optimal theoretical energy consumption** using the HDD model [67].

Finally, regarding the Case Base that will be used, an **initial set of Cases** has to be created. The initial Case Base will be extracted from **historical data** derived from tracking the **energy-behavior of the user**.

- Over a period of time (e.g. six months) the COSMOS Cloud will accumulate readings for **Tin**, **Tout**, **consumption** and **flow rates** (for fixed intervals).
- From these data, for these specific time intervals (half-hour), cases will be created, having as:
  - **Problem: Tin_initial**, **Tin_final** (sensors), **Tout** (sensor/website)
  - **Solution: IoT-service** (up/down), **Consumption** (EnergyHive)

To sum up, the several steps that the Application Developer should take are:

- stating which data (and how) are forwarded to the **Cloud**: readings from sensors, the EnergyHive, the weather website etc.
- stating how the **CB** is created (what will be its **format**).
- stating how the **Problems** are **defined** by the user input.
- providing the internal logic/code of the Application. For example, he/she states how the **maximum consumption** is derived by the budget (e.g. using data from the energy-provider website).
- providing the GUI for the scheduling input and the report form for the outcomes.
- stating which properties of the VE (domain ontology) are important for finding similar friends.

On the other hand, COSMOS:

- offers to the App-developer **cloud storage**.
- by using CBR, helps the App-developers create **simple** Applications without having to create physical or mathematical models (**straightforward problem statement/solving**) or care about how the best solutions are found.
- by offering a **social community** to the VEs, makes sure that, if a good solution is available, it can be found. Offering optimal available solution.
- by offering **feedback mechanisms** (from the user or the system itself) the available knowledge can be refined.

10. Conclusion

In this document we analyzed some of the main mechanisms and tools that we will develop in order to provide in Y3 a complete **coordination framework** for managing the network of Things considering different administrative rules, locations, reputation and trust patterns, as well as IoT application requirements and interactions between the Things. These mechanisms and tools will allow Things to react in an **autonomous** and predictive way based on the information retrieved from other Things experiences, enable **runtime adaptability** of the network and **decentralized discovery** of various entities and create a **social environment** for the Things. An evolved version of the main functional components of WP5 (like the Planner) was presented and the relations between the different components were further described.

The main new feature that is introduced in this deliverable is the social side of COSMOS. The COSMOS platform can be characterized as a SIoT platform since it defines, monitors and exploits social relations and interactions between Things and uses technologies from the domain of the social media. The social side of COSMOS improves the knowledge flow and the sharing of services between Things, a really important characteristic for the constant evolution of the IoT systems. To sum up, in this deliverable we go beyond the state of the art by:

- identifying and establishing social properties and relations between VEs in such a way that the resulting social network is effectively manageable;
- describing a decentralized IoT architecture which supports the functionality required to form a social network following the Social Internet of Things paradigm. We discuss some services and mechanisms, like distributed relations management and decentralized discovery mechanisms;
- studying social analysis metrics and properties and identifying roles for the VEs and desired functionalities for our components;
- creating a new Trust & Reputation model addressing most of the security threats that apply to distributed knowledge systems.

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