A Declarative Goal-oriented Framework for Smart Environments with LPaaS

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Abstract—Smart environments powered by the Internet of Things aim at improving our daily lives by automatically tuning ambient parameters (e.g. temperature, interior light) and by achieving energy savings through self-managing cyber-physical systems. Commercial solutions, however, only permit setting simple target goals on those parameters and do not consider mediating conflicting goals among different users and/or system administrators, and feature limited compatibility across different IoT verticals. In this article, we propose a declarative framework to represent smart environments, user-set goals and customisable mediation policies to reconcile contrasting goals encompassing multiple IoT systems. An open-source Prolog prototype of the framework is showcased over two lifelike motivating examples.

Index Terms—Goal-oriented systems, Smart Environments, Internet of Things, Logic Programming, LPaaS

I. INTRODUCTION

The Internet of Things (IoT) is continuously growing and becoming an integrated part of our daily lives with a plethora of new different applications (e.g. smart-environments, wearable, home appliances) [1], [2], that show even capable of affecting our mood [3]. Among the new verticals the IoT is enabling, smart environments are getting increasing attention from the market and the research community [4], [5]. Indeed, they empower private and public ambient to self-manage cyber-physical systems (e.g. A/C, lights, plants watering) based on data from IoT sensors, triggering reactions enabled by IoT actuators. Besides their high potential to improve people’s routines, these applications can also lead to a more sustainable energy and resource management [4], [6].

Especially for those applications that include human goals in the self-management loop of smart environments, the problem of reconciling contrasting goals among different users emerges clearly [7], [8]. Colleagues sharing a room in a public building – even for a limited amount of time – can possibly express very different desiderata on the temperature and on the light intensity they prefer to experience while they work. To this end, many techniques have been proposed to reconcile such contrasting goals set by users or system administrators, e.g. via fuzzy logic [9], multi-agents systems [10], [11] or neural networks [12]. However, most commercial solutions, such as IFTTT [13] or Amazon Alexa [14], only allow setting simple goals to be met by the IoT systems they manage and do not consider the possibility of mediating among contrasting objectives [15].

Additionally, despite being deployable out-of-the-box by their final users, existing commercial solutions show inherent limitations, mainly due to their proprietary nature. These limitations prevent them to be extended and from work across IoT verticals enabled by different vendors. They also make it difficult to develop policies to mediate between users and administrator objectives, i.e. set local and global goals. Factually, two different types of conflict can arise:

User-user – Different users can set different goals on their desired state of the environment (e.g. on target temperature),

User-admin – The System Administrator can set global objectives that must be met (e.g. on maximum energy consumption, on law constraints), which may conflict with the user-set goals.

Even after reconciling the previous types of conflicts into one target state satisfying all set (user and/or global) goals, a final configuration of the actuators involved must also be determined. Indeed, given a final target state, we need to (a) determine the correct configuration for each actuator acting on that state, and (b) mediate between any conflicting configurations that a single actuator possibly receives.

In this article, we propose a declarative methodology to specify customisable mediation policies for reconciling contrasting goals and actuator settings in smart environments. The methodology can solve contrasting goals by reasoning on the available IoT infrastructure and on (possibly contrasting) goals set by the users and by system administrators. The novel contribution mainly consists of:

(1) a declarative framework to specify mediation policies for reconciling contrasting (user and/or global) goals and actuator settings in smart environments,

(2) a Prolog prototype implementation of (1), Solomon, provisioned as a REST service by relying on Logic Programming-as-a-Service (LPaaS) [16].

Solomon tames the effects of the aforementioned types of conflict by allowing to flexibly specify ad-hoc mediation policies for distinct zones of a smart-environment and possible conflicting settings of target actuators. Such policies can resolve conflicts (i) among users’ goals, (ii) among users’ and system administrator’s goals, and (iii) on actuators configuration. Last, but not least, the declarative nature of Solomon makes it easy to write, maintain and extend arbitrary mediation policies encompassing multiple IoT verticals.
The rest of this article is organised as follows. After illustrating two motivating examples (Sect. [II]), we give some background on Prolog (Sect. [III]). Then, we present our methodology for goal mediation and its prototype (Sect. [IV]), showcasing them over the first motivating example. The full prototype is subsequently assessed over the second motivating example (Sect. [V]). Finally, we discuss some closely related work (Sect. [VI]) before concluding (Sect. [VII]).

II. MOTIVATING EXAMPLES

In this section, we illustrate two scenarios from smart environments to better highlight the need for reasoning solutions capable of mediating among contrasting goals and encompassing different IoT verticals. The first scenario considers a room in a Smart Home (Sect. II-A), while the second scenario, on a larger scale, considers a floor of a Smart Building made of many offices and rooms (Sect. II-B). Both examples consider two main stakeholders:

**User** – a human or digital agent that can set goals on the ambient around them, aiming at creating the most comfortable environment for them to live in,

**System Administrator** – a human or digital agent that can define conflict resolution policies, and set global goals on the smart environment (e.g. on energy saving).

A. Smart Home

Consider a shared room in a student apartment, equipped with three lights – a main light, a bed light and a corner light – and an A/C system. In this case, depending on the time of day and the activity that is taking place (e.g. studying, watching a film, reading a book), different lighting configurations could be required. Conflicts might arise as, for instance, it can happen that Alice wants to watch a movie while Bob is still studying in the same room. Moreover, Alice might prefer to stay in a cool room (20°C) while Bob prefers a warmer ambient (26°C).

Natural questions raised by the above scenario are:

- **Is it possible to find a configuration of the three lights which allows Alice and Bob to comfortably carry on their different activities?**
- **Is it possible to find a configuration of the A/C system which mediates among the preferences of Bob and Alice on the environment temperature?**

B. Smart Building

Consider now the smart building floor sketched in Fig. 1 consisting of a West and East wings. The West wing is exposed to light most of the day while the East wing is less illuminated. In each wing, there are 5 rooms (4 single and one shared), the single rooms in pairs share the air conditioning system and the relative temperature sensor. Also, each room has a large light and a desk light and a brightness sensor. The shared rooms have two large lights and their air conditioning system as well as a temperature sensor and a brightness sensor. Additionally, the first single room in the East wing has also a small heater. Finally, each user has assigned a single room and has full access to both shared. Furthermore, targeting sustainability, company policies require that the temperature in the environment stays within 18°C and 22°C in autumn and winter, and between 24°C and 28°C in spring and summer. Also in these settings, some questions arise such as:

**Q1** How to describe the available Smart Building so that it is possible to apply ad-hoc policies for the West and East wings?

**Q2** How can we specify policies to manage temperature and brightness in the different rooms of the building, handling conflicts so to ensure the comfort of its inhabitants and to meet sustainability policies?

**Q3** Once a target state has been found for a specific room, how to determine suitable settings of the available (shared and non-shared) actuators to achieve it?

All questions raised above highlight the need for novel models and methodologies to flexibly manage smart environments, such as the one we propose in this article. In the next section, we will detail our proposal by relying on the Smart Home example. The Smart Building example will be used instead in Sect. [V] to assess the methodology over a larger scale scenario.

III. BACKGROUND: PROLOG & LPaaS

Prolog is a logic programming language as it is based on first-order logic. A Prolog program is a finite set of clauses of the form:

\[ a : = b_1, \ldots , b_n. \]

stating that \( a \) holds when \( b_1 \land \cdots \land b_n \) holds, where \( n \geq 0 \) and \( a, b_1, \ldots, b_n \) are atomic literals. Clauses can also contain inclusive disjunctions (i.e. logic ORs) among literals \( b_i \) and \( b_j \), represented by \( b_i \lor b_j \). Clauses with empty condition are also called facts. Prolog variables begin with upper-case letters, lists are denoted by square brackets, and negation by \( \neg \).

Recently, Calegari et al. [16] have proposed to realise LPaaS, offering a flexible and lightweight inference engine as a REST service. LPaaS wraps a Prolog engine inside a REST server to manage incoming requests consistently. Such a service offers a well-defined API to upload Prolog facts and clauses that solve a domain-specific problem, to trigger reasoning over them, and to obtain computed solutions. LPaaS can be easily configured to handle stateful and stateless reasoning tasks, with static or dynamic knowledge bases.

![Fig. 1. An example of Smart Building](image-url)
Overall, LPaaS aims at enabling a plethora of different applications among ubiquitous and smart IoT systems, e.g. domestic robot assistants, smart kitchens to handle food supply based on user preferences, reasoning in sensor networks. Particularly, [7] shows how LPaaS is well-suited for smart IoT applications and complex wireless networks, thanks to its high interoperability and customisation.

IV. METHODOLOGY AND PROTOTYPE

In this section, we illustrate Solomon, a declarative framework featuring autonomic goal mediation in smart environments, in presence of multiple users. The framework is prototyped and open-sourced[1] in Prolog, using LPaaS. We first give an overview of the architecture we foresee for Solomon to be deployed (Sect. IV-A), then we detail the model (Sect. IV-B) and methodology (Sect. IV-C) underlying our framework.

A. Overview

Fig. 2 gives a bird’s-eye view of the architecture of Solomon. Solomon interacts with a smart environment, consisting of IoT sensors and actuators (or the services they are wrapped in). Indeed, Solomon periodically receives updated data from the sensors deployed in the smart environment, depending on which it can trigger suitable actions for the available actuators.

We call property types the elements in such a dictionary, assuming they are declared as in

propertyType(TypeId).

where TypeId is a literal value denoting the unique property type identifier. Given a propertyType we can then define actuators and sensors that sense or operate on that.

Actuators are declared as in

actuator(ActuatorId, TypeId).

where ActuatorId is the unique actuator identifier and TypeId is the associated property type.

Analogously, sensors are declared as in:

sensor(SensorId, TypeId).

where SensorId is the unique sensor identifier and TypeId is the associated property type. Environmental values monitored by each sensor are denoted by

sensorValue(SensorId, Value).

where SensorId identifies the sensor and Value is the last value it read.

Example. Based on the above, the shared room of the Smart Home example of Sect. II-A can be declared as in

propertyType(light).

propertyType(temp).

sensor(brightness, light).
sensor(temperature, temp).
sensorValue(brightness, 20).
sensorValue(temperature, 22).

actuator(smallLight, light).
actuator(mainLight, light).
actuator(cornelLight, light).
actuator(ac, temp).

where two sensors measure two different property types (i.e. temperature and brightness), having three lamps that can act on brightness and the AC system capable of changing the temperature. Please note that the current temperature settles at 22°C and the brightness at 20 out of 255.

System administrators can divide smart environments into different zones, which allow distinguishing which global policy to apply to specific sets of sensors and actuators.

zone(ZoneId, MediationPolicy).

where ZoneId is the unique zone identifier and MediationPolicy is the unique identifier of the global management policy the zone is subject to. A zone groups one or more property instances, defining a set of actuators and a set of sensors that operate on a specific property type. A property instance is declared as in

propertyInstance(ZId, PIId, TypeId, Actuators, Sensors).

where ZId identifies the zone to which the instance belongs, PIId is the property instance identifier, TypeId is the propertyType of PIId, Actuators is a list of actuators that operate on the property and Sensors is a list of sensors that monitor it within the zone. All actuators and sensors in a given property instance must have the same property type. The identifier of a property instance is unique only within the zone, allowing for distinct zones to have instances with the same identifier.

1Freely available at: https://github.com/di-unipi-socc/Solomon

Fig. 2. Blackbox view of Solomon

Both users and system administrators interact with Solomon, through the LPaaS API or through available UIs. On one hand, users can declare goals on the target state they wish to experience while being in the smart environment. On the other hand, system administrators can declare global mediation policies to solve user-user conflicts, to set global goals and solve user-admin conflicts, and to determine actuator configurations useful to reach a target state for the smart environment, after goal mediation. Note that Solomon is provisioned as a service, enabled by an LPaaS engine, which allows (i) to easily integrate it with other pieces of software such as user interfaces (UIs) or mobile applications and (ii) to deploy it either to Cloud or Edge servers, depending on the usage context.

B. Model

Smart Environment. To model smart environments, we first build up a dictionary of all types of environmental parameters we can monitor (via sensors) and/or act upon (via actuators).
Example. The property instances of the Smart Home example can be described by declaring a single livingroom zone and, for instance, four property instances as in

```
zone(livingroom, _).
propertyInstance(livingroom, studyingLight, light, [cornerLight, mainLight], [brightness]).
propertyInstance(livingroom, movieLight, light, [cornerLight, smallLight], [brightness]).
propertyInstance(livingroom, readingLight, light, [smallLight], [brightness]).
propertyInstance(livingroom, roomTemp, temp, [ac], [temperature]).
```

It is worth noting that the first three property instances all refer to the light property, grouping the brightness sensor with the lamps needed to realise different settings on such property, e.g. for studying (cornerLight and mainLight), watching a movie (cornerLight and smallLight), or reading a book (smallLight only). The last property instance refers instead to the temp property, grouping to the temperature sensor and the A/C system (i.e. ac).

Users and Goals. A user is declared as in

```
user(UserId, AllowedZones).
```

where UserId is the unique user identifier and AllowedZones is the list of the zones on which the user can set goals. User goals are declared as in

```
set(UId, ZId, PIId, Value).
```

where UId is the user identifier, ZId identifies a zone, PIId is one of the property instances of the zone, and Value is the goal expressed by the user on the property instance.

Example. Still following the Smart Home scenario, Alice and Bob, and their goals on brightness and temperature are represented as per

```
user(alice, [livingroom]).
set(alice, livingroom, movieLight, 20).
set(alice, livingroom, roomTemp, 20).
user(bob, [livingroom]).
set(bob, livingroom, studyingLight, 80).
set(bob, livingroom, roomTemp, 26).
```

Alice aims at setting the movieLight property instance to 20 out of 255 and the roomTemp to 20°C. Bob, on the contrary, wants to set the studyingLight property instance to 80 out of 255, and the roomTemp to 26°C.

C. Reasoner

The model described up to now denotes the inputs that Solomon receives from the smart environment it manages as well as from its users. Fig. 3 lists the core code of Solomon, which works in three main steps that constitute the top-down methodology of the proposed framework to determine a target state for a smart environment. Those steps are as follows:

1) it collects all user requests that are currently submitted to the system (getRequests/2, line 2) and extracts only those that are valid,
2) it mediates requests referring to the same property instance by applying the mediation policies specified by the system administrator, so to determine a target state for each property instance (mediateRequests/2, line 3) by solving all user-user and user-admin conflicts,
3) it finally determines actions (i.e. settings) for individual IoT actuators so to achieve the target state, by also resolving possible conflicting actions found for a single actuator (associateActions/2, line 4).

Overall, the react/3 predicate (line 1) returns three lists: the list of all Requests, the list of MediatedRequests containing the target states for each property instance and the list of actions to perform to reach a final target state. It is worth noting that, while the framework leaves complete flexibility to the system administrators in defining their own mediation policies, it also checks that inputs and outputs of each phase are well-formed (through predicates validMediation/1, line 3, and validActions/1, line 4). This guides the system administrators in their task of writing (formally) valid mediation policies.

collecting Requests. First, Solomon collects all the requests through getRequests/2 (line 2, lines 5–9), which determines two lists of tuples (ZId, PIId, Value, UId), where each tuple corresponds to a set(UId, ZId, PIId, Value) with arguments rearranged for easier handling in later stages. The first list Requests contains all current requests from users (line 6). The second one, ValidRequests, only contains valid requests (line 7–9), i.e. by default requests for which the zone and the property instance exist, and the zone is among those the user associated with the request can set goals on.

Example. In the Smart Home scenario, querying

```
?- getRequests(Requests, ValidRequests).
```

returns the following:

```
Requests = ValidRequests,
ValidRequests = [(livingroom, movieLight, 20, alice),
(livingroom, studyingLight, 80, bob),
(livingroom, roomTemp, 20, alice),
(livingroom, roomTemp, 26, bob)].
```

collecting all requests from Alice and Bob. Mediating Requests. Valid requests are then passed to the mediateRequest/3 predicate (line 3) which can be flexibly and freely specified by the system administrator. The objective of this phase is to mediate between the possible conflicting goals of the users by determining one target value for each property instance. The mediateRequests/2 predicate outputs a list MediatedRequests of such values for each property instance, in the form of triples (Zoneld, PropertyInstanceId, Value). Then, the validMediation/1 predicate (lines 3, 10–13) checks that the list contains no duplicates (line 12) and that all requests are still valid after mediation (line 13).

Example. In our Smart Home scenario, a possible mediateRequests/2 that simply averages user requests for a same property instance is as follows:

```
mediateRequests(Requests, Mediated) :-
  groupPerPI(Requests, NewRequests),
  validMediation/1(Mediated).
mediateRequests/2
```

3System administrators can easily extend the concept of valid request by including further checks based on domain-specific knowledge, e.g. on the range of allowed values for a given property. This can be done by extending the validRequest/3 predicate exploited by getRequests/2 (line 8).
react(Requests, MediatedRequests, Actions) :-
\+( ( member((A,V), OrderedActions), \+( validValue(A,V) ) ) ),
\+( ( member((A,V1), OrderedActions), member((A,V2), OrderedActions), dif(V1,V2) ) ),
ValidRequests).

sort(Reqs, OrderedReqs),
validMediation(Reqs) :-
( member((ZId, PIId, Value, UId), Requests), user(UId, Zones), member(ZId, Zones), validRequest(ZId, PIId, Value) ),
findall( (ZId, PIId, Value, UId), \+( ( member((Z,PI,V), OrderedReqs), \+( validRequest(Z,PI,V) ) ) )).
validActions(Actions) :-
findall((ZId, PIId, Value, UId), set(UId, ZId, PIId, Value), Requests),
associateActions(MediatedRequests, Actions), validActions(Actions).
getRequests(Requests, ValidRequests) :-
\+( ( member((Z,PI,V1), OrderedReqs), member((Z,PI,V2), OrderedReqs), dif(V1,V2) ) ),
getRequests(Requests, ValidRequests),
mediateRequests(ValidRequests, MediatedRequests), validMediation(MediatedRequests),
ValidRequests).

mediateRequest(NewRequests, Mediated).

mediateRequest([Z,PI, Rs]|Reqs), [Mediated|OtherMedReqs] :-
\+( \+ ( member((Z,PI, V), OrderedReqs), \+ ( member((Z,PI,V2), OrderedReqs), dif(V1, V2) ) ) ),
\+ ( \+ ( member((Z,PI,V), OrderedReqs), \+ ( validRequest(Z,PI,V) ) ) ).
validActions(Actions) :-
\+( Actions, OrderedActions),
\+( ( member((A,V), OrderedActions), member((A,V2), OrderedActions), dif(V1, V2) ) ),
\+( ( member((A,V), OrderedActions), \+ ( validValue(A,V) ) ) ).

First, for each input requests, a triple (Zone, PropertyInstance, TargetValue), actionsFor/2 gets the list of actuators of that specific propertyInstance. Then, it selectActuatorsForPI/6 computes the list of actions to be performed by dividing the target value for each propertyInstance by the number of its actuators. Note that when an actuator belongs to more than one propertyInstances, setActuators/2 selects the highest value available cutting that value with a lower bound of 0 and an upper bound of 100.

By querying setActuators/2 in the Smart Home scenario, given the target state of the previous example, we obtain:

Note that the ac actuator is set to 23°C, i.e. the value of the target state. As for movieLight and studyingLight, being composed of several actuators, a further mediation happens. The target value of 20 for movieLight is split across cornerLight and smallLight, setting each to 10. Analogously, the target value of 80 for the studyingLight is split across mainLight and cornerLight, setting each to 40. The conflict on cornerLight, being in both property instances, is solved by picking the maximum between 10 and 40, viz. 40.

Fig. 3. Solomon code.
V. SMART BUILDING EXAMPLE RETAKEN

In this section, we exploit Solomon to answer the specific questions raised about the Smart Building scenario of Sect. II-B.

The answer to Q1 is obtained by first specifying different zone(ZoneId, MediationPolicy) facts for the rooms in the smart building (Fig. 1), as in

\[
\text{zone(room} \_\text{E} \_1, \text{east}). \\
\text{zone(room} \_\text{E} \_2, \text{east}). \\
\text{zone(room} \_\text{E} \_3, \text{east}). \\
\text{zone(room} \_\text{E} \_4, \text{east}). \\
\text{zone(room} \_\text{W} \_1, \text{west}). \\
\text{zone(room} \_\text{W} \_2, \text{west}). \\
\text{zone(room} \_\text{W} \_3, \text{west}). \\
\text{zone(room} \_\text{W} \_4, \text{west}). \\
\text{zone(commonRoom} \_\text{E}, \text{east}). \\
\text{zone(commonRoom} \_\text{W}, \text{west}).
\]

The east and west literals identify two different mediation policies, specified by System Administrator, to be applied to the property instances grouped under the zone. Such grouping can be obtained by specifying suitable propertyInstance(2Id, PIId, TypeId, Actuators, Sensors) facts as, for instance, in

\[
\text{propertyInstance(room} \_\text{E} \_1, \text{roomTemp, temp, [acOdd}_\text{E}, \text{heater], [tempOdd}_\text{E}]). \\
\text{propertyInstance(room} \_\text{E} \_1, \text{roomLight, light, [biglightRoom} \_\text{E} \_1, \text{smalllightRoom} \_\text{E} \_1], [lightRoom} \_\text{E} \_1]). \\
\text{propertyInstance(room} \_\text{E} \_3, \text{roomTemp, temp, [acOdd}_\text{E}, \text{heater], [tempOdd}_\text{E}]). \\
\text{propertyInstance(room} \_\text{E} \_3, \text{roomLight, light, [biglightRoom} \_\text{E} \_3, \text{smalllightRoom} \_\text{E} \_3], [lightRoom} \_\text{E} \_3]).
\]

that describes the sensors and actuators available in the Room 1 and Room 3 of the East wing. Note that the two rooms share the acOdd_E actuator for the A/C system and that Room 1 contains the heater actuator that is not available in Room 3.

Based on the knowledge representation above, we can now answer Q2 by suitable implementations of mediateRequests/2. Indeed, the System Administrator can easily declare mediation policies to solve user-user and user-admin conflicts in a context-aware manner. Such behaviour can be obtained through predicate mediateRequests/2 (which is used by mediateRequests/2 as illustrated in Sect. IV):

\[
\text{mediateRequests(Z, MediationPolicy, Prop, V, Actuators, Actions) :-} \\
\text{findValue(V, member(Prop, Values), Values),} \\
\text{avg(Values, AvgTemp),} \\
\text{forAll(A, member(A, Actuators), triggerAll(A, V, L, Actuators)).}
\]

First mediateRequests/2 averages all user requests for a specific property instance so to mediate possible user-user conflicts. Then, it exploits findValue/4 to mediate between the obtained average with the global policy enforce by the System Administrator. Such mediation is based on the MediationPolicy of the zone (i.e. east, west), on the property type Prop (i.e. light, temp) on the value obtained by the sensor of that instance (i.e. SensedValue) and on the computed average value AvgTemp.

Fig. 4 lists the code of predicate findValue/4. The first clause of findValue/4 (lines 1–4), manages the temperature in both wings in the same way. After determining the current season (line 2), it enforces that the target value is within the season-dependent ranges specified for sustainability purposes (line 3–4), viz. 18–22°C in Winter and Autumn and 28–24°C in Summer and Spring. The second and the third clauses of findValue/4 (lines 5–6 and 7–10) manages instead the environmental brightness, depending on the wing of the room, on the current brightness and the weather. This process determines a mediated target state that reconciles all user-user and user-admin conflicts on each property instance, which fully answers Q2.

Finally, the answer to Q3 is obtained by first specifying different zone(ZoneId, MediationPolicy) facts for the rooms in the smart home (Fig. 1), as in

\[
\text{zone(room} \_\text{E} \_1, \text{east}). \\
\text{zone(room} \_\text{E} \_2, \text{east}). \\
\text{zone(room} \_\text{E} \_3, \text{east}). \\
\text{zone(room} \_\text{E} \_4, \text{east}). \\
\text{zone(room} \_\text{W} \_1, \text{west}). \\
\text{zone(room} \_\text{W} \_2, \text{west}). \\
\text{zone(room} \_\text{W} \_3, \text{west}). \\
\text{zone(room} \_\text{W} \_4, \text{west}). \\
\text{zone(commonRoom} \_\text{E}, \text{east}). \\
\text{zone(commonRoom} \_\text{W}, \text{west}).
\]

The east and west literals identify two different mediation policies, specified by System Administrator, to be applied to the property instances grouped under the zone. Such grouping can be obtained by specifying suitable propertyInstance(2Id, PIId, TypeId, Actuators, Sensors) facts as, for instance, in

\[
\text{propertyInstance(room} \_\text{E} \_1, \text{roomTemp, temp, [acOdd}_\text{E}, \text{heater], [tempOdd}_\text{E}]). \\
\text{propertyInstance(room} \_\text{E} \_1, \text{roomLight, light, [biglightRoom} \_\text{E} \_1, \text{smalllightRoom} \_\text{E} \_1], [lightRoom} \_\text{E} \_1]). \\
\text{propertyInstance(room} \_\text{E} \_3, \text{roomTemp, temp, [acOdd}_\text{E}, \text{heater], [tempOdd}_\text{E}]). \\
\text{propertyInstance(room} \_\text{E} \_3, \text{roomLight, light, [biglightRoom} \_\text{E} \_3, \text{smalllightRoom} \_\text{E} \_3], [lightRoom} \_\text{E} \_3]).
\]

that describes the sensors and actuators available in the Room 1 and Room 3 of the East wing. Note that the two rooms share the acOdd_E actuator for the A/C system and that Room 1 contains the heater actuator that is not available in Room 3.

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\[
\text{mediateRequests(Z, MediationPolicy, Prop, V, Actuators, Actions) :-} \\
\text{findValue(V, member(Prop, Values), Values),} \\
\text{avg(Values, AvgTemp),} \\
\text{forAll(A, member(A, Actuators), triggerAll(A, V, L, Actuators)).}
\]

First mediateRequests/2 averages all user requests for a specific property instance so to mediate possible user-user conflicts. Then, it exploits findValue/4 to mediate between the obtained average with the global policy enforce by the System Administrator. Such mediation is based on the MediationPolicy of the zone (i.e. east, west), on the property type Prop (i.e. light, temp) on the value obtained by the sensor of that instance (i.e. SensedValue) and on the computed average value AvgTemp.

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Finally, the answer to Q3 is achieved through the implementation of the associateActions/2 predicate. In our Smart Building, the policy we chose to adopt consists of dividing the workload equally between the various actuators, with the only exception of the heater that only accepts two values, viz. 0 or 100. The code is similar to the one proposed in the previous section for the Smart Home, in which the selectActionsForPI/6 is adapted to the new policy and in case of multiple requests to the same actuator, now the maximum value is chosen.

First selectActionsForPI/6 computes the number of actuators of the propertyInstance (i.e. L), then triggerAll/4 is called which distributes the workload to the actuators with the exception of the heater. Finally, setActuators choose the maximum in case of multiple sets for a specific actuator (with no lower or upper bound). With this process we can determine the correct configuration for each actuator acting on that state, and mediate between any conflicting configurations that a single actuator possibly receives, answering to Q3.

We conclude this section by describing a use case for the scenario above exploiting the policies described. Suppose that it is a sunny day in winter, with the brightness value sensed in the West common room at 160 out of 255, and user u1 sets the brightness of her room to 0 and the temperature to 18°C. On the contrary, user 3 sets the temperature at 28°C. Assume that the two rooms share the A/C system but not the lighting system. Meanwhile, user 4 sets the temperature and brightness of room 2, which is she is not authorised to handle. Finally, users u2 and u8 are both in the commonRoom_E with the same goal for the light but different goals for the temperature (respectively 23°C and 18°C).
findValue(_, temp, _, TempValue, Value) :-
    season(S),
    ((S = winter ; S = autumn), (TempValue > 22, Value is 22; TempValue < 18, Value is 18; Value is TempValue));
    ((S = summer ; S = spring), (TempValue > 28, Value is 28; TempValue < 24, Value is 24; Value is TempValue)).

findValue(east, light, _, LightValue, Value) :-
    (LightValue > 255, Value is 255; LightValue < 100, Value is 100; Value is LightValue).

findValue(west, light, _, LightValue, Value) :-
    (LightValue > 255, Value is 255; LightValue < 180, Value is 180; Value is LightValue).

E (LightValue > 255, Value is 255; LightValue < 100, Value is 100; Value is LightValue).

W ((Brightness > 100, (LightValue > 255, Value is 255; LightValue < 100, Value is 100; Value is LightValue));
    ((Brightness > 100, (LightValue > 255, Value is 255; LightValue < 100, Value is 100; Value is LightValue));
    (LightValue > 255, Value is 255; LightValue < 180, Value is 180; Value is LightValue)).

Fig. 4. findValue/4 implements global policies in the Smart Building.

For each room the result of the mediation phase with the application of global policies described before is:

\[
[(\text{room}_E_1,\text{roomLight},100), (\text{room}_E_1,\text{roomTemp},18),
(\text{room}_E_3,\text{roomTemp},22), (\text{commonRoom}_W,\text{commonRoomLight},255),
(\text{commonRoom}_W,\text{commonRoomTemp},20.5)]
\]

where \text{roomLight} of \text{room}_E_1 is bounded on 100 because it is the minimum bound for the light in the East wing, while the \text{roomTemp} is within the bounds. Meanwhile, \text{roomTemp} of \text{room}_E_3 is bounded to 22 the maximum temperature allowed in winter. Instead in commonRoom\_W the temperature is the average of the two requests because it is within the boundaries and also the light because we are in the West wing and it is sunny (brightness \geq 100) so the maximum bound is 255, the goal of both users. Finally, the goals of user u4 are ignored because is not authorised to interact with \text{room}_E_2. Then, the actions to be carried out, given the states computed, will be:

\[
[(\text{acCommonRoom}_W, 20.5), (\text{biglightCommonRoom}_W_1, 127.5),
(\text{biglightCommonRoom}_W_2, 127.5), (\text{acOdd}_E, 22), (\text{heater}, 100),
(\text{biglightRoom}_E_1, 50), (\text{smalllightRoom}_E_1, 50)]
\]

where the temperature of \text{commonRoom}_W is managed only by \text{acCommonRoom}_W and the light is implemented by two main light which equally divide the goal. Meanwhile, \text{acOdd}_E is the air conditioning system shared by room 1 and 3 and is setted to the maximum of the two goals (18 and 22) and also in \text{room}_E_1 the heater is working. Finally, the small and big light work together to implement the goal.

VI. RELATED WORK

In this section, we discuss some closely related work on the self-management of smart environments. Most of these works fall within three main categories, viz. goal-oriented [18], hierarchical [19], and neural and fuzzy [20].

First, [21]–[24] and [25] propose goal-oriented approaches to conflict mediation. Targeting global goals as energy efficiency, users comfort, and system security, [21] presents a solution to manage smart buildings by adding a semantic layer on top of the stack of IoT devices for reaching the desired global goals, exploiting an ontology of goal types. With a more formal approach, [22] devise a methodology for autonomic device management describing the evolution of a smart environment as the set of evolutions of single device states, modelled as command sequences. Given a global goal, this solution determines the correct sequence of commands to reach it. Besides, [23] proposes an access control mechanism exploiting a priority-based policy negotiation technique to solve user-user conflicts in a smart home, made of multiple devices. Finally, Tartarus [25], is a Prolog platform designed to integrate cyber-physical systems and robots, supporting mobility, cloning, and payload carrying. More in general, [24] propose a solution for the problem of conflicts resolution in a multi-agent system, through argumentation-based reasoning. Naturally, as per its goal-oriented nature, Solomon enables system administrators to write customised policies that can accommodate sophisticated and expressive mediation policies exploiting for example the semantic ontology described in [21] or the negotiation technique proposed in [23].

Second, hierarchical solutions for goal mediation have been proposed by [19] and [26]. Dynamic hierarchical goal management for different IoT systems is discussed in [19], considering conflicting local and global goals, and the availability of limited resources that can vary at runtime. Regarding security in smart environments and in particular Smart Offices, [26] propose a hierarchical, agent-based solution that considers the high number of potential users, their security roles and the heterogeneity of devices and spaces. An interesting extension to Solomon is to include hierarchical approaches to solve goals and to consider security aspects as well.

Third, and last, fuzzy logic [9], [27], [28] and neural network [12], [29] approaches to goal mediation have been studied recently, along with their combination [30]. Fuzzy logic can be used for context-awareness in Smart Home as illustrated in [27], where raw data from the sensors are processed to manages actuators according to the computed context based on the user movement and activity. The works in [9], [28] propose expert systems to control the A/C of smart buildings, based on the current status of the sensors and the outside temperature. Similarly, [30] manages A/C systems through a neuro-fuzzy controller where an adaptive neural network is used to better tuning the fuzzy rules, making them...
more robust. Neural networks have also been successfully used to predict energy consumption more reliably than traditional techniques \cite{28} and for indoor temperature forecasting \cite{29}. As Prolog is well-suited to implement fuzzy logic \cite{31}, an interesting extension of Solomon is to accommodate fuzzy controllers. Similarly, predictions based on neural networks can be made available in the knowledge base of Solomon from external services or by relying on recent implementations of Prolog that support neural networks (e.g. DeepProbLog \cite{32}).

VII. CONCLUDING REMARKS

This article proposed a declarative framework – and its open-source Prolog prototype Solomon – to specify policies for mediating contrasting (user and/or global) goals and actuator settings in smart environments. The prototype is provisioned as a service through LPaaS, and it can resolve user-user and user-admin conflicts into a target state for the smart-environment and a set of actuators settings to reach it.

The wide variety of smart environments and the desiderata of their users and system administrators calls for new frameworks to easily develop and continuously adapt domain-specific mediation policies. This work moves some first steps towards this direction, aiming at contributing a novel declarative approach, enabled by LPaaS, to the field of goal-driven management of smart environments. As showcased in our example, thanks to its declarative nature, Solomon features a suitable level of abstraction and flexibility to accommodate different needs of smart environments, making it easy to express, maintain and update mediation policies as per the ever-changing needs of IoT scenarios.

In our future work, we intend to:

- **New Policies.** Implement and test other mediation policies (e.g. based on fuzzy logic, learning or heuristics), by also proposing a set of building blocks that System Administrators can use to compose their own policies.

- **Goal Geolocation.** Model a geo-localisation system for users and exploit machine learning to predict their movements and preferences, to reduce manual interaction.

- **Web of Things.** Integrate Solomon with Web of Things to make it more interoperable and easier to exploit in existing smart environments.

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